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Argillic horizons and clay-sized particles - an alternative interpretation of their dynamics in sola development and across catenas

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**Argillic horizons and clay-sized particles – an alternative interpretation of
their dynamics in sola development and across catenas**

By

Mostafa Abdelssamie Abdelkhalik Ibrahim

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Soil Science (Soil Morphology and Genesis)

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Chapter 1. General introduction

Introduction

Soil is one of the main resources for most terrestrial life. Soil Sciences study soils from many different perspectives. They are very important for agriculture, construction and mining. Agriculturally, Soil Science has two main branches, Edaphology and Pedology. Edaphology was defined by Porta and others (1994) as “the study of the community of microflora and microfauna in the soil (edaphon) and the processes that govern their existence and development (edaphogenesis)”. Pedology was defined by Gregorich and others (2001) as “the study of soils that integrates their distribution, formation, morphology and classification as natural landscape bodies”.

This dissertation has two overarching aims: (1) to better understand how and where the argillic horizon forms; and, (2) to better understand how the clay-sized fraction of soil behaves within the sola and catenas of Iowa.

As pedologists, we are interested in studying argillic horizons because they have unique characteristics that formed by different mechanisms of clay accumulation. The argillic horizon is a subsurface diagnostic horizon of clay accumulation (Soil Survey Staff, 2010). Formation of the argillic horizon has been investigated for decades. Pedologists attribute the formation of argillic horizon to three different mechanisms: (a) translocation of clay particles from eluvial horizons to illuvial horizons – that is lessivage, (b) neoformation and (c) transformation of primary minerals in the subsurface horizons (Schaetzl and Anderson, 2005). For a subsurface horizon to be considered as an argillic horizon, it must have clay

films and a specific content of clay compared to the overlying horizons (Soil Survey Staff, 2010).

In this dissertation I investigated the occurrence and distribution of argillic horizons across the contiguous US in order to capture a general concept about the factors that affect its formation. My data showed that argillic horizons can occur almost everywhere across the contiguous US. Forty percent of the US soils have argillic horizons. The places lacking argillic horizons tend to be areas which have sand dunes, rocky mountains, steep slopes and places with plenty of prairie potholes. Therefore, I focused on the Midwest States because there is a large spot lacking argillic horizons and yet it is surrounded by them. More specifically, I investigated the origin and distribution of argillic horizons across Iowa and the relationship between drainage systems and the formation of argillic horizons. It is discussed in chapter two of this dissertation.

For the second part of the study, I investigated the possible movement directions of clay-sized particles. Four demonstrations were performed in this work. First, I tested the likelihood of upward movement of clay in sponges. The results demonstrated the possibility of upward movement. Second, I tested for upward movement of clay in sand columns. Basically, I set a number of clean and transparent plastic bottles that have holes in them at the bottom in aluminum pans and then filled them with pure medium quartz sand. Next, I supplied clay suspension to the aluminum pans so that clay suspension gets into sand columns from the bottom. Clay suspension moved upwards through sand columns and then accumulated at the top of them.

To apply the results of the second step in real soils, I tried to mimic nature by establishing a water table level in sand columns. Clean sand layers were interspersed with sandy loam layers in transparent plastic bottles that stood in glass beakers. Next, I added water to the beaker so that water got into the sand columns from the bottom. The results of this step demonstrated both downward and upward movement of clay-sized particles. Also, these results demonstrated the likelihood of clay movement by diffusion. I used the results of this work to introduce an alternative mechanism for the formation of lamellae.

In chapter four, I investigated some pedons that have argillic horizons in them. One pedon was used from the following eight counties – Mahaska, Monroe, Davis, Jefferson, Van Buren, Keokuk, Lucas and Marion. This area was selected because it has soils that have shale in their sola. All of the pedons were completely described and analyzed. All of these study pedons were formed in layered parent materials such as Pennsylvanian Shale, Peoria Loess, glacial till or local colluvium. The results of field descriptions and laboratory analyses were used to classify study pedons down to the family level. These study pedons were classified to two main soil orders, Alfisols and Ultisols. Moreover, the occurrence of lithologic discontinuities in these pedons was tested using different methods such as total sand, sand: silt ratio as well as total silt as a depth functions.

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Chapter 2. Origin and distribution of argillic horizons across Iowa

– A novel hypothesis

Mostafa A. Ibrahim and C. Lee Burras

A paper submitted to Soil Science Society of America Journal (SSSAJ)

Abstract

Argillic horizons are distributed across much of the world. They are common in 43 of the 48 contiguous states of the USA. In Iowa, soils with argillic horizons cover 33.5 % of the land area. Fifty-nine percent of the area in Iowa with argillic horizons is in Alfisols (Udalfs and Aqualfs). The remaining 41 % is in Argiudolls, Argiaquolls and Argialbolls. At the county level, the prevalence of argillic horizons varies widely. Many eastern and southern Iowa counties have around 90% of their soils with argillic horizons. Some central and western Iowa counties have almost no soils with argillic horizons. We hypothesize that the presence of argillic horizons in Iowa is largely a function of two controls: (a) Si-consumption by hydrophytic organisms and (b) prevalence of secondary Ca-minerals in some closed depressions. Both controls are predicated on catena drainage. Our methodology was to compile pedologically relevant data and pedon descriptions from a variety of databases and then to use GIS to facilitate spatial interpretations. Our findings agree with the concept that mature forest and prairie catenas in open drainage systems generally have soils with well-expressed argillic horizons across the whole soil catena. In contrast, our findings are soils in catenas in closed drainage systems very rarely have argillic horizons and where they do, they are Argialbolls. The biotic (i.e., active pedogenic factor) contrast between the open and closed catenas appears to be the prevalence of silicon hyperaccumulators such as reeds,

sedges and cattails. Also, calcareous Aquolls in closed catenas promote formation of calcium silicate which is a passive sink for silicon.

Introduction

The argillic horizon is a subsurface diagnostic soil horizon with clay accumulation of defined magnitude (Soil Survey Staff, 1999). It is extensive worldwide, being found in humid through arid regions (Allen and Fanning, 1983; Gile and Grossman, 1968). Argillic horizons likely develop through one or more of the following three processes: clay translocation, clay transformation or clay neoformation (Smeck et al. 1968; Nettleton et al., 1975; Egli et al., 2001).

Clay translocation, a.k.a. lessivage, is generally described as beginning with chemical or physical dispersion of fine clays along a macropore, followed by downward movement as suspended load in leaching pore water and ending with deposition (e.g., see, Eswaran and Sys, 1979; Miller, 1983; Phillips, 2007). The depth of clay deposition in the solum is thought to be controlled by wherever pore size becomes so small as to constrict water flow – e.g., a pore is partially plugged by illuviated clays from prior episodes of translocation – or, porewater is pulled into side pores via capillarity which leaves the clays lining the original macropore (Thorp and Smith, 1949), or, by flocculation as the clays encounter increased soil pH and ionic strength in the lower solum. These ideas are consistent with Rousseau and others (2004), who - in a laboratory experiment using an intact soil column and repeated water additions from a rainfall simulator - found translocation of clay depends on the intensity of rainfall, ambient moisture content, occurrence of continuous macropores that originate at the soil surface, soil structure, ionic strength of pore solution and phyllosilicates

mineralogy and size. Moody (2006) stated that clay films are usually deposited on macropore walls when percolating water is drawn through micro pores as a result of the matric suction. As Miller (1983) notes, pedologists accept clay translocation as being an almost certain process in formation of many argillic horizons.

Mineral transformation during pedogenesis is another mechanism of argillic horizon formation. For example, silt-sized mica can weather in situ to clay-sized illite, which increases the clay content of the horizon (Jackson, 1965). This process has also been shown to occur with feldspars weathering to halloysite and kaolinite (McCaleb, 1959; Allen and Fanning, 1983; Islam et al, 2002). An example of this was reported by Prychid and others (2004) according to the following reaction:



It is pedologically important to recognize that as primary minerals weather they are not only producing in situ secondary minerals but they are also releasing – in one form or another – Al, Fe, Mg, or Ca. The example of Prychid and others (2004) shows the production of eight moles of silicic acid in solution per mole of kaolinite formed. These solutes ultimately must migrate somewhere, with most eventually recrystallizing into neoformed minerals, which are generally clay-sized (Michalopoulos and Aller, 1995; Charlet and Manceau, 1994).

As alluded to in the previous paragraph, silicon is of special interest to our hypothesis because silicic acid, H_4SiO_4 , is a prevalent component of most soil solutions (Dove, 1995). Its critical role in pedogenesis is well recognized albeit often not explicitly

considered even though Si is the major cation in the majority of minerals present in soil. Sommer and others (2006) in their review paper noted that solution Si produced during pedogenesis may migrate into or out of ground water. Many studies have shown solution Si can be chemically adsorbed on calcium carbonate surfaces (Sommer et al., 2006); reacts with calcium, forming calcium silicate minerals (Maxim et al., 2008); or can be biologically taken up by plants and returned to the soil as crystalline phytoliths in litter (e.g., Blecker et al., 2006). Moreover, solution Si can be directly biologically precipitated in a crystalline form as sponges and diatoms (Blecker et al., 2006). These biogenic pools, in turn, weather and return the Si to the soil solution although the kinetics of their dissolution is poorly understood (Blecker et al., 2006). Epstein (1994) found that SiO_2 concentration in plant tissues ranges from 0.1 to 10 % on a dry weight basis while Marschner (2006) reported that wetland vegetation generally contains 10 to 15 % SiO_2 on dry weight basis. Marschner's (2006) results suggest that hydrophytes use Si as a nutrient which, in light of the preceding literature review, suggests they influence silicate stability and instability in soils.

The aim of this study is to develop a hypothesis that explains argillic horizon distribution across Iowa in a manner consistent with pedological theory and known silicon dynamics.

Materials and methods

Our methods entailed three phases of data mining - nationwide, regional, within Iowa. First, we documented where argillic horizons occur across the contiguous USA in order to discern the conditions favoring their formation. Second, we examined argillic horizons occurrence in a subset of counties around Iowa in order to evaluate this occurrence regionally

and evaluate the impact of the pedological factors on the formation of the argillic horizons. Third, we focused on Iowa in order to distill why argillic horizons are extensive in some regions and rare in other ones.

We established the distribution of soils with argillic horizons across the contiguous USA by using the NRCS Soil Extent Mapping Tool (Soil Survey Staff, 2010a), which is maintained at Pennsylvania State University website (<http://www.cei.psu.edu/soiltool/>). We did this through a series of iterations using all taxonomic groups that include argillic horizons. For example, we obtained maps of all Alfisols and Ultisols. Likewise in Mollisols and Aridisols, we obtained all maps of Argiudolls, Argiustolls, Argixerolls, Argialbolls, Argiaquolls, Argicryolls, Argiborolls, Argids, Argidurids, Argicryids and Argigypsid. Subsequently, we took each of the 13 maps we obtained from Soil Extent Mapping Tool and combined them into a GIS shape file that we georeferenced and digitized. Finally, the digitized layers were stacked into a single map that shows the distribution of argillic horizons across the contiguous USA (Figure 2.1). It is important to note a limitation of our approval counties into two categories: counties with more than 4000 hectares of soils with argillic horizons and others with less than 4000 hectares of soils with argillic horizons.

Our second level of data mining consisted of examining central USA trends in argillic horizons. Soil data of seventeen counties from the states surrounding Iowa were collected by downloading the online soil survey manuscripts facility (Soil Survey Staff, 2010b). the dominant vegetation map of the Midwest states was obtained from the website established by Students Allied for a Greener Earth (SAGE, 1991) after we verified it from Jenny (1941) and

a series of modern vegetation atlases. The map was scanned and saved as a TIF file, added to a GIS file, georeferenced and then digitized.

The last level of data mining was within Iowa. Our goal in this level was to discern the distribution of argillic horizons across Iowa. We used the Iowa Soil Properties and Interpretations Database (ISPAID). We added the ISPAID table to our GIS shape file and then used the query definition to extract the areas with argillic horizons as text files. Text files were opened in Excel files in order to calculate and classify the areas with argillic horizons. Occurrence of argillic horizons in every county in Iowa was calculated as percentage relative to the county area. Similarly, the occurrence of argillic horizons across the state was calculated as a percentage relative to the whole area of the state. After doing all of the calculations using Microsoft Excel and definition queries in ArcGIS, we established our Iowa's soils database that has all of the information about soils with or without argillic horizons. Then, we linked this database to Iowa's map using ArcGIS 9.3.

Finally, we examined three counties – Marshall, Guthrie and Webster from Iowa in detail to test and explain the relationship between the argillic horizon formation and open and closed drainage systems. We selected these counties because they have comparable mean annual temperature, mean annual precipitation and a prevalence of grassland as native vegetation (Table 2.3). The digital maps of these three counties were obtained from the Natural Resources Geographic Information Systems Library (2010). The Des Moines Lobe (DML) area was digitized from landform regions of Iowa map (Prior, 1991).

Results and discussion

There are 4,000 ha or more of soils with argillic horizons mapped in at least 2,940 of the 3,111 counties in the contiguous USA (Figure 2.1). The 4,000 ha value was used to rapidly create a general argillic occurrence map across the USA. Our first observation regarding Figure 1 is argillic horizons clearly occur across a wide range of the USA – and by extension – across a wide range of parent materials, geomorphic surfaces, vegetations and climatic conditions. Our second observation is argillic horizons are absent in part of the Midwest, especially northwest Iowa, southwest Minnesota, southeast South Dakota and far eastern Nebraska. Three geological provinces are included in this region: (a) Late Wisconsinan Loess Hills, (b) Missouri River valley and (c) – most extensively – Des Moines Lobe. The Missouri River Valley is filled with recent alluvium, which we interpret means there has not been adequate time for argillic horizon pedogenesis. The Loess Hills are prevalent in far western Iowa and have steep and sharp slopes (Iowa Department of Natural Resources Staff, 2011; Prior, 1991). As a result the Loess Hills have one of the highest rates of soil erosion in the U. S., approximately, $99 \text{ ton ha}^{-1} \text{ y}^{-1}$ (USGS, 2011). Consequently, the region's soils exhibit AC or ABwC profiles (Oschwald et al., 1965).

The other part of Iowa with a paucity of argillic horizons is the DML, which is a Late Wisconsinan glacial surface that is geomorphically similar to the Late Wisconsinan glacial surfaces of Illinois, Indiana and Ohio. This surface in these other states commonly has soils with argillic horizons. The Iowa-Minnesota-Dakota region differs from those eastern states in their ecology and hydrology, i.e., the presence of prairie potholes (Stewart and Kantrud, 1971). Within and surrounding the prairie potholes are silicon-loving organisms that are adapted to live in wet conditions. In addition, calcareous soils surround these potholes. Khan

and Fenton (1994) attributed the formation of secondary calcium carbonates in the upper parts of the sola – e.g., Canisteo series – to the discharge of shallow water table. This shallow water table has soluble calcium bicarbonate that precipitates as calcium carbonate in the sola due to evapotranspiration, desiccation and outgassing.

In order to understand why argillic horizons are scarce on the DML, we examined 17 counties from outside of it and Iowa. Our goal was to better understand what soil forming factors likely control argillic horizon formation in the central USA. These 17 counties were chosen to represent the range in Midwest climate, biota and parent materials (Figure 2.2, Table 2.1, and Table 2.2). Mean annual temperature ranges from 2.6 °C to 13.8 °C in the 17 counties. Similarly, there is a wide range of mean annual precipitation, 449 to 981 mm per year. The predominant native vegetation is limited to prairie and deciduous forest. The major parent materials include till, lacustrine, residuum, alluvium and loess.

Data in Table 2.1 show that grass ecosystems apparently yields argillic horizons. Likewise, low mean annual precipitation does not seem to preclude the formation of argillic horizons. For example, Clay and Fillmore Counties in Nebraska receive less than 700 mm of mean annual precipitation yet have more than 90% of their soil areas with argillic horizons. All of these argillic horizons occur in Mollisols at locations that have been grassland ecosystem since the dominant Peoria Loess parent material was deposited. This suggests forests and high rainfall are not necessary for the argillic horizons formation but rather they simply seem to accelerate its formation. Rather – to sum up Table 2.2 – argillic horizons occur everywhere around Iowa with no easy correlation to pedogenic factors.

Within Iowa, approximately, 33.5% of the land area has soils with argillic horizons. Udalfs and Aqualfs comprise almost 59 % of the soils with argillic horizons. Mollisols (Argiudolls, Argiaquolls and Argialbolls) represent the remaining 41 % of the soils with argillic horizons. The majority of the soils with argillic horizons occur in eastern and southern Iowa (Figure 2.3), where some counties have approximately 90% of their soil area with argillic soils. On the other hand, few soils with argillic horizons occur in the western and northern parts of Iowa. For example, some counties have 0 % soils with argillic horizons such as Sioux, Plymouth, Monona and Harrison counties. We attribute this paucity to the erosion and deposition processes that take place in this area causing the Missouri Alluvial Plain and Loess Hills geomorphic surfaces to be young. In other words, the argillic horizon formation did not have enough time to be developed.

To evaluate the relationship between closed depressions and argillic horizons across the landscape, we examined three counties in Iowa. These counties are Marshall, Guthrie and Webster Counties (Figure 2.3). We selected these counties because they have comparable mean annual temperature, mean annual precipitation and a prevalence of grassland as native vegetation (Table 2.3). Each county also has both open and closed drainage systems (Figures 2.4, 2.5 and 2.6). The geomorphic surfaces of the DML and Southern Iowa Drift Plain (SIDP) both geomorphically stabilized at about the same time, i.e., about 3,000 to 6,000 years (Ruhe, 1968). In other words, the DML and SIDP are distinct physiographic provinces yet only really differ in terms of two interrelated pedological factors. These are relief and biota. Overall, the DML has closed drainage systems with shallow water tables that result in

a prevalence of hydrophytes and diatoms while the SIDP has open drainage systems that result in more mesic biota and fewer hydrophytes and diatoms.

Exemplifying both regions is Marshall County which has 49% of its land area covered by soils with argillic horizons (Figure 2.4). The vast majority of them occur on the SIDP, primarily in Mollisols. A second county split by the region is Guthrie County. It has 55 % of its soils with argillic horizons - 35 % is Alfisols and 65 % is Mollisols (Table 2.3 and Figure 2.5). We noticed an area that lacks argillic horizons within it between the DML part and SIDP part. This area is occupied by Webster and Clarion soil map units which means the approximate boundary of the DML could be displaced from the right position. In both counties most argillic horizons occur in the SIDP where open drainage systems predominate. Conversely, we rarely find argillic horizons in the parts of the two counties located inside the DML, which is where closed depressions with their Si-loving organisms predominate.

Traditionally, Iowa pedologists have surmised from soils in counties like Guthrie and Marshall that the DML is somehow pedologically limiting argillic horizons formation. In order to test the impact of the DML on argillic horizon formation we chose Webster County. It is located entirely inside the DML. Also, a major river runs through it, which is the Des Moines River that is younger in age than the Late Wisconsinan till (Bettis and Mandel, 2002). Closed depressions across most of Webster County are ubiquitous yet a few areas with argillic horizons exist. The majority of argillic horizons existing in Webster County occur along the Des Moines River where the open drainage occurs (Figure 2.6). The few closed drainage systems that have argillic horizons have Argialboll series such as the Rolfe

mapped within them. Our observation is these Argialbolls are often adjacent to soils that formed in outwash (Cylinder series). Hence, we attribute the occurrence of these Argialbolls to the outwash causing groundwater hydrology to behave as if is in open drainage systems, i.e., they are recharge wetlands (Figure 2.7).

In closed depressions, there is not enough downward movement of water because most of the ground water is a discharge type. Since clay particles follow the water flow pathways, clay downward movement is not enough to form the argillic horizon. In addition, dissolution of CaCO_3 produces Ca^{++} and HCO_3^- ions that make the ionic strength of soil solution to be high enough to inhibit clay particles to be dispersed. Consequently, clay translocation from the upper horizons to the lower horizons is precluded.

We would be remiss if we did not note that closed depressions not adjacent to outwash or alluvium have calcareous soils such as Harps and Canisteo within them (Figure 2.8). The pH in these soils is high enough to make the weathering of primary minerals to be slow. In other words, the formation of clay particles by the transformation process of primary minerals to secondary minerals is diminished. Similarly, slow weathering of minerals diminishes the production of solution Si which results in decreasing the likelihood of neoforming clay particles.

Herein, we are summarizing the relationship between occurrence of argillic horizons and both closed and open drainage systems across the landscape. In closed drainage systems, Si-demanding organisms such as cattails, reeds, sedges, diatoms and sponges exist. These organisms are high Si consumers. Plants can take up Si and precipitate it in their bodies as phytoliths. Diatoms and sponges precipitate Si in their bodies as well. When these plants die,

they return silicon as phytoliths to the soil. However, the dissolution rate of phytoliths is less than the silicon uptake rate of plants (Blecker et al., 2006). We anticipate it is equally true for sponges and diatoms. Consequently, silicon coming from phytoliths, sponges and diatoms dissolutions is not sufficient for the Si demands of new plants. Numerically, cattails can take up Si from the hydric soils in large amounts. For example, Solano and others (2004) in their constructed wetland in the north central part of Spain under a Mediterranean climate, revealed that cattails can consume $558 \text{ ton ha}^{-1} \text{ 3000y}^{-1}$ of silicon; this number becomes larger with adding the consumption of Si by diatom's frustules and sponge's specules. That results in mining silicon from the landscape and thus precluding new clay minerals to form. Blecker and others (2006) suggested that if clay minerals are neoformed, solution silicon will be depleted from the system. That means if other factors like Si-loving organisms and calcareous conditions deplete this solution silicon from the system, the likelihood of forming clay minerals will be smaller and – we hypothesize - even the detrital fine clays may be destabilized. In other words, both mechanisms of fine clay enrichment common to argillic horizons are reduced.

In addition, formation of Ca-silicate secondary minerals and occurrence of calcium carbonates preclude the formation of argillic horizon by the following mechanisms: (1) Ca-compositions react with silicic acid forming Ca-silicate minerals and then inhibit clay neoformation; (2) adsorption of Si on the calcium carbonate particles; and (3) high ionic strength of the soil solution inhibits the clay particles to be dispersed and then precluding them from moving downward through the translocation process.

In contrast, open drainage systems under prairie normally have few Si-loving organisms and minimal formation of Ca-carbonate and Ca-silicate secondary minerals. Therefore, either lessivage of detrital fine clay and/or neoformation can readily occur. Additionally, forest consistently favors argillic horizons formation irrespective of drainage conditions. This is because trees in general take up less silicon compared with hydrophytic plants. For instance, Lucas (2001) addressed that deciduous forest can take up $135 \text{ ton ha}^{-1} 3000 \text{ y}^{-1}$ of silicon. That is perhaps one-quarter the amount of silicon taken up by hydrophytic organisms of the prairies and wetlands.

Conclusions

Argillic horizons occur almost everywhere across the contiguous USA. Closed depressions – because of their Si loving organisms and, possibly, the occurrence of secondary Ca-silicate minerals – largely preclude the argillic horizon formation.

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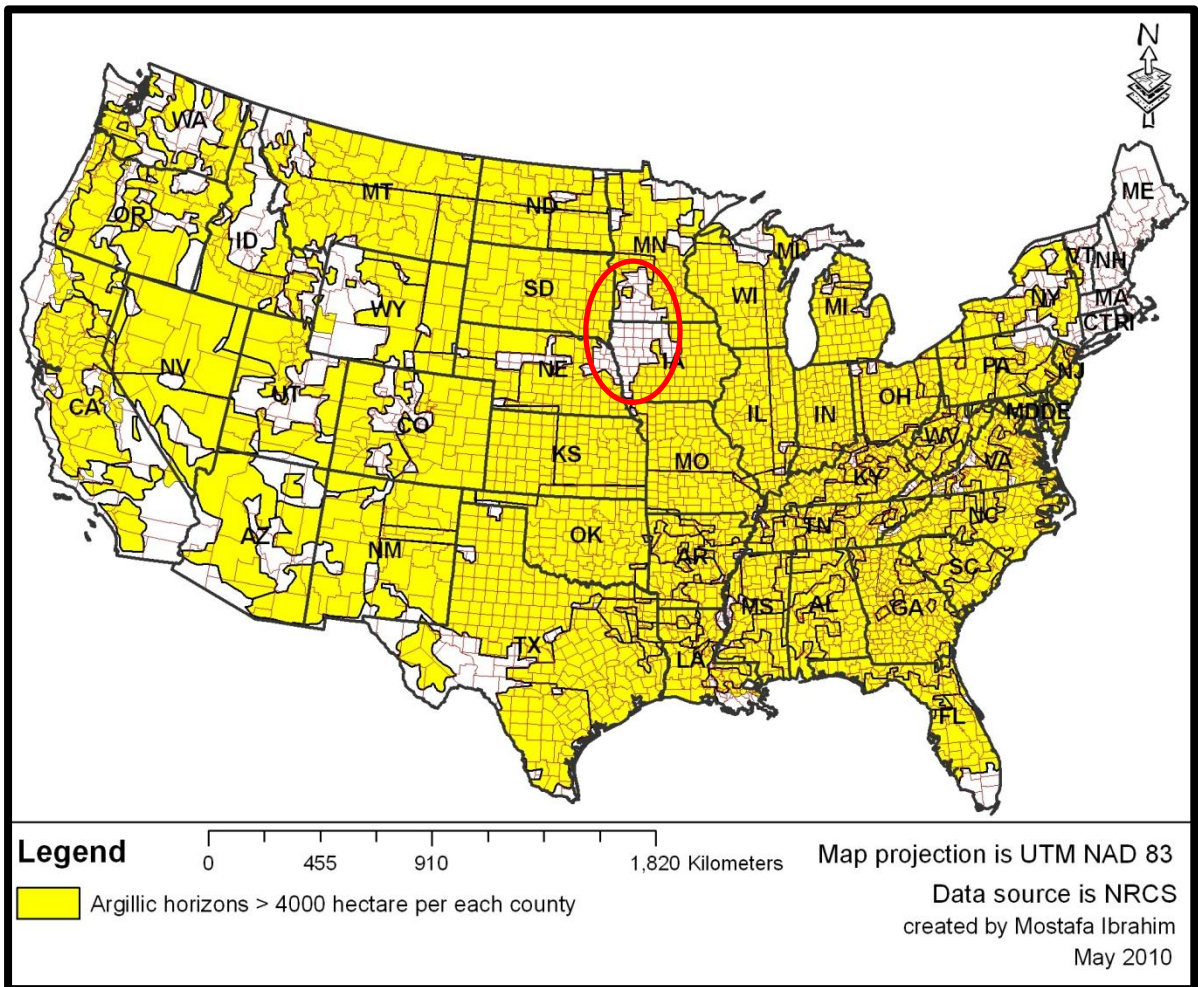


Figure 2.1. Occurrence of argillic horizons across the contiguous USA.

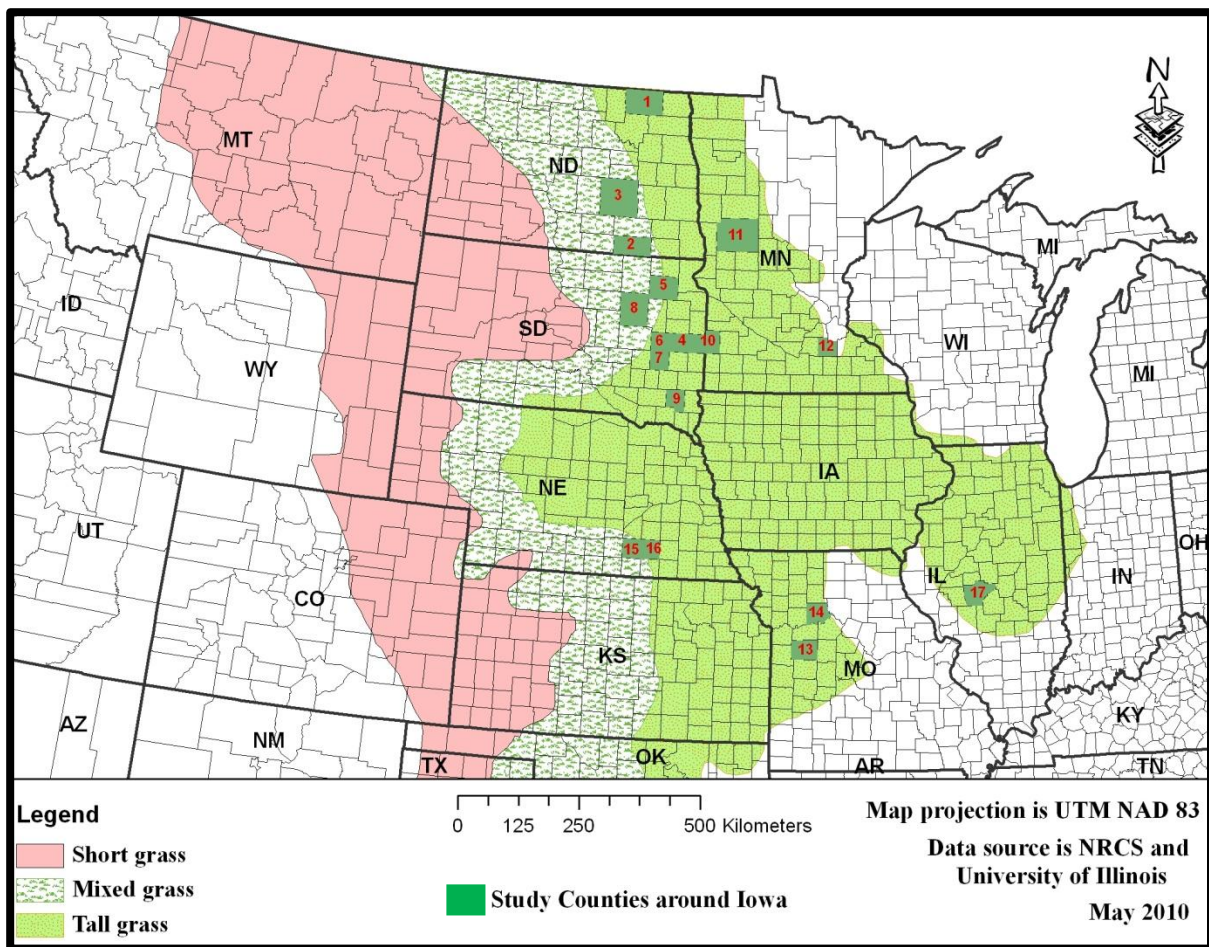


Figure 2.2. Study counties around Iowa and their natural ecosystems.

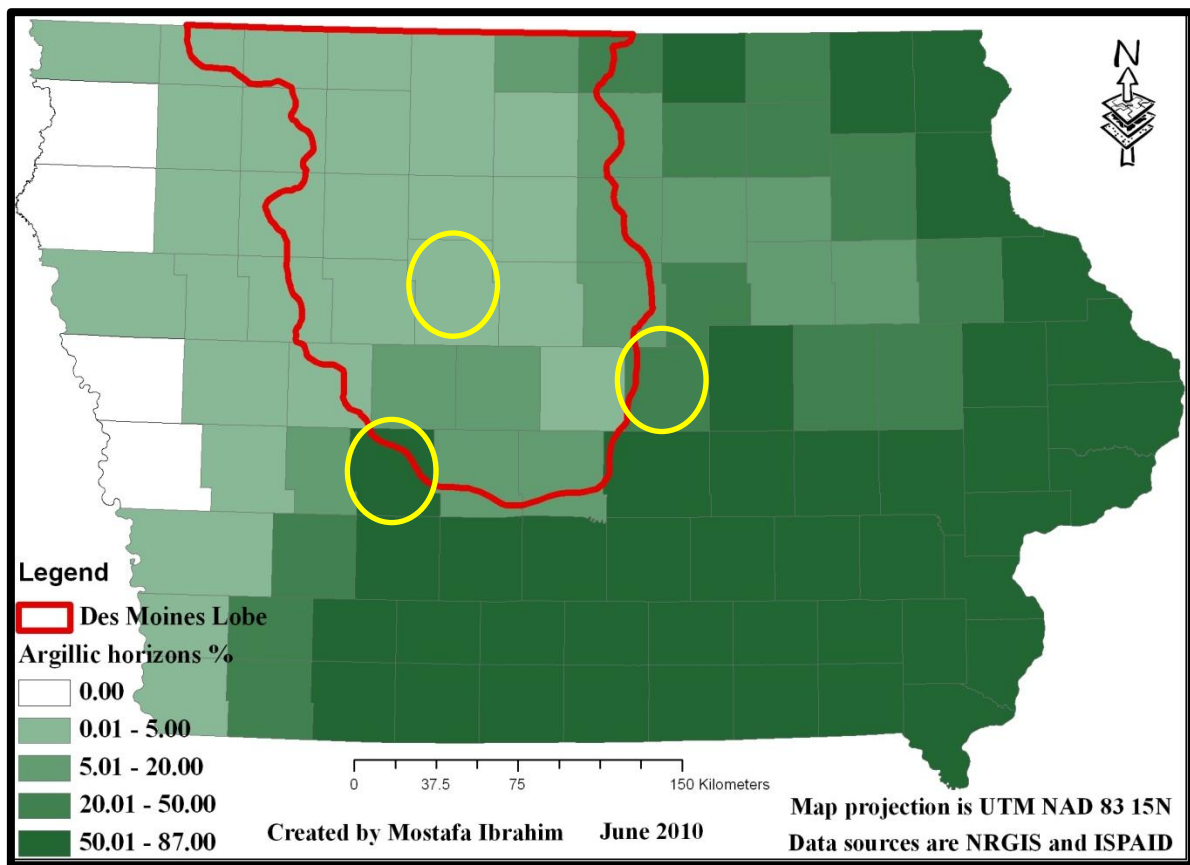


Figure 2.3. Prevalence of argillic horizons across Iowa.

Percentage value in the legend refers to the percentage in each county and was calculated as follows:

$\% \text{ of argillic horizons} = \text{area of soils with argillic horizons} / \text{total area of the county} \times 100.$

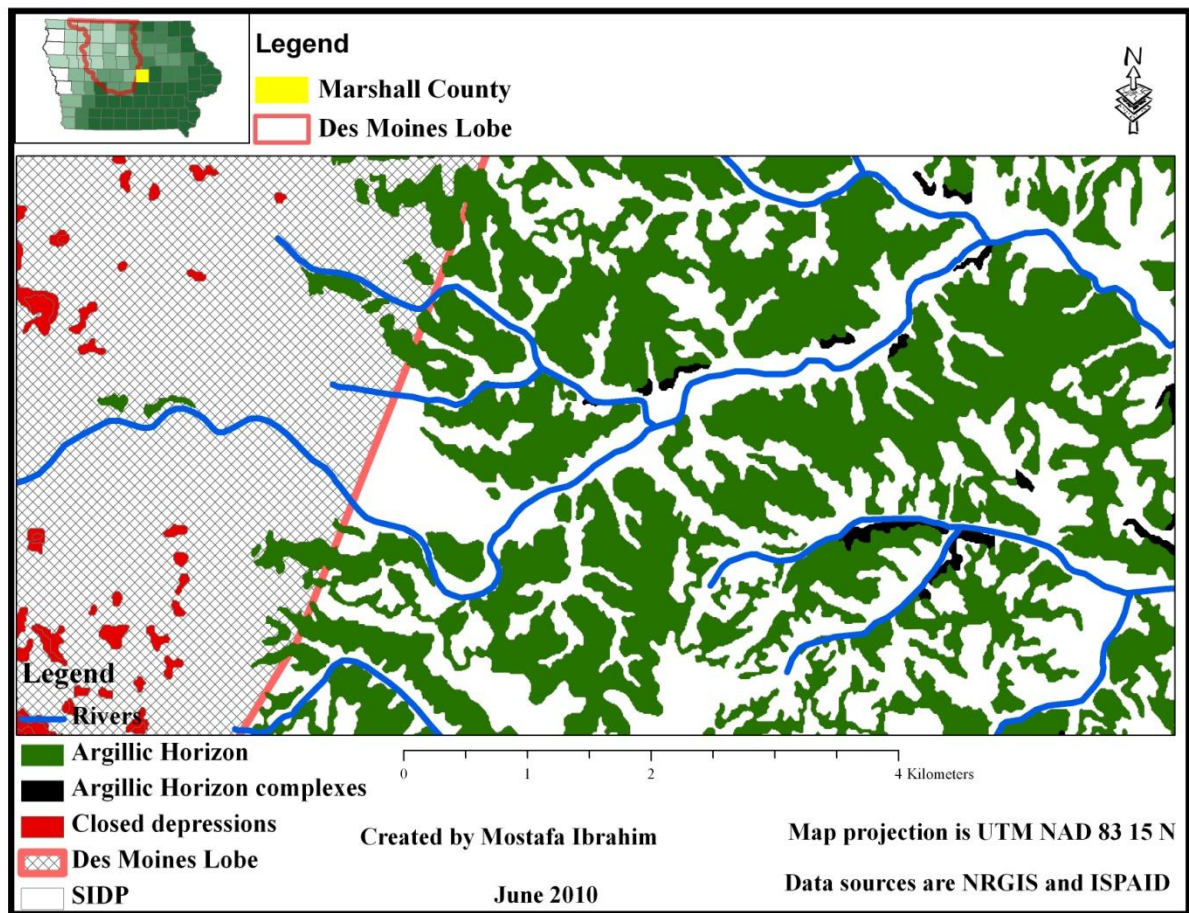


Figure 2.4. Distribution of argillic horizons across the western part of Marshall County, Iowa.

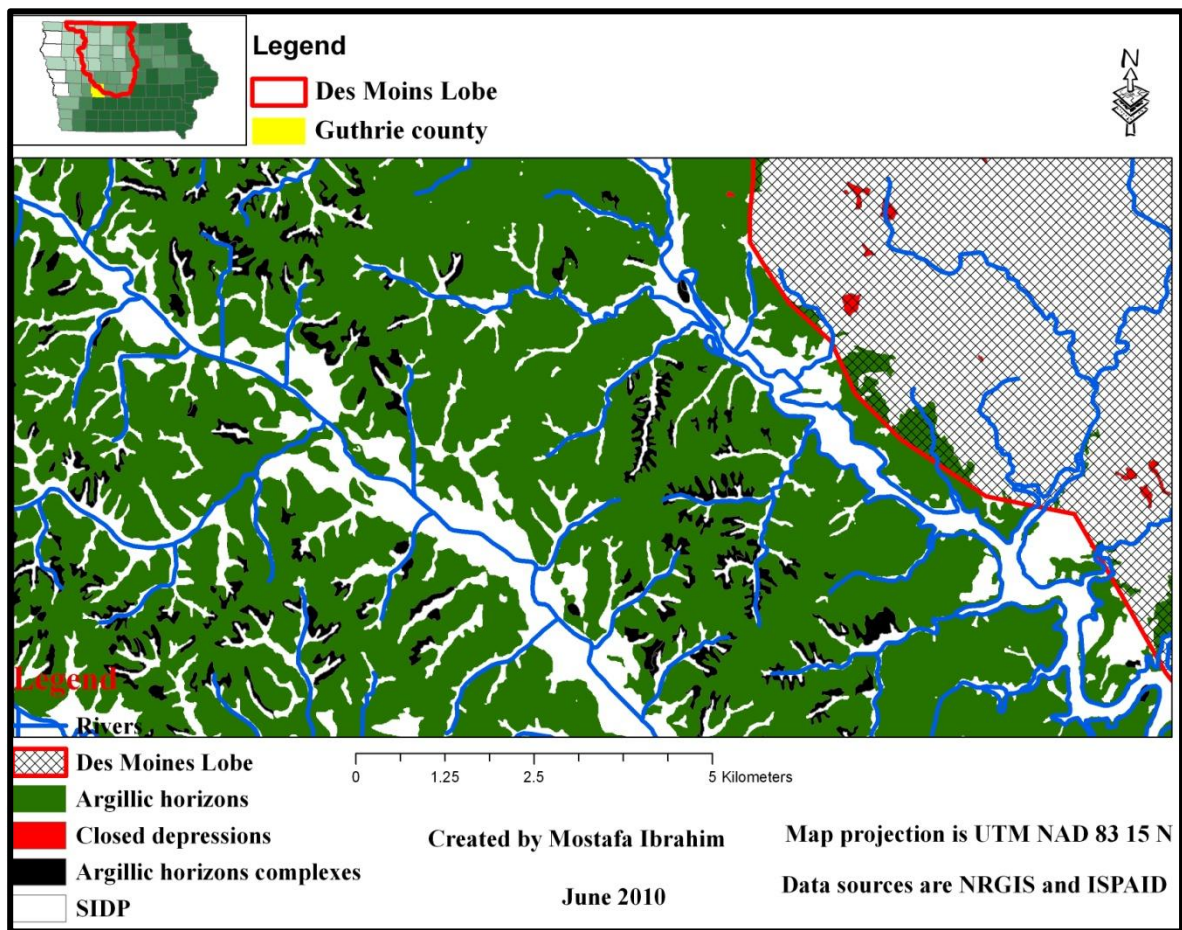


Figure 2.5. Distribution of argillic horizons across the eastern part of Guthrie County, Iowa.

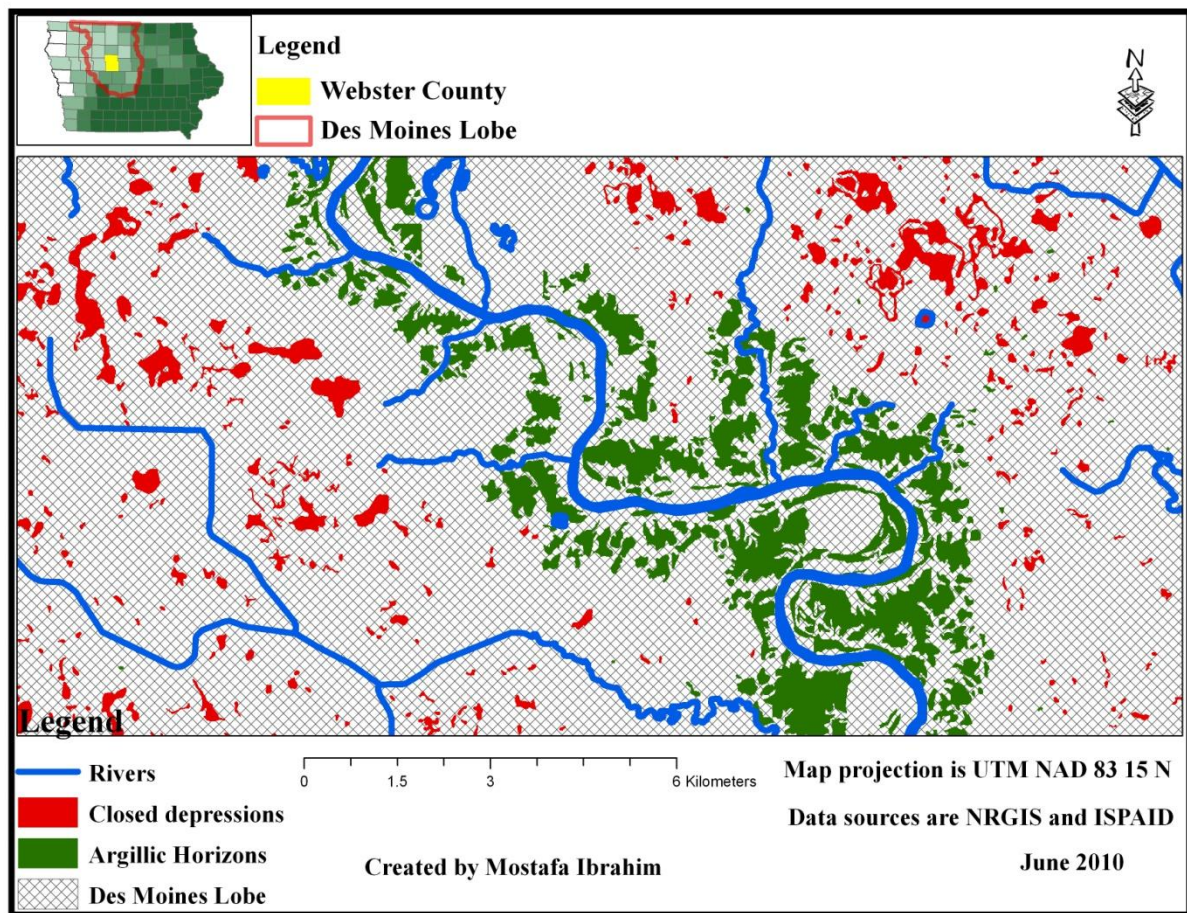


Figure 2.6. Distribution of argillic horizons across central part of Webster County, Iowa.

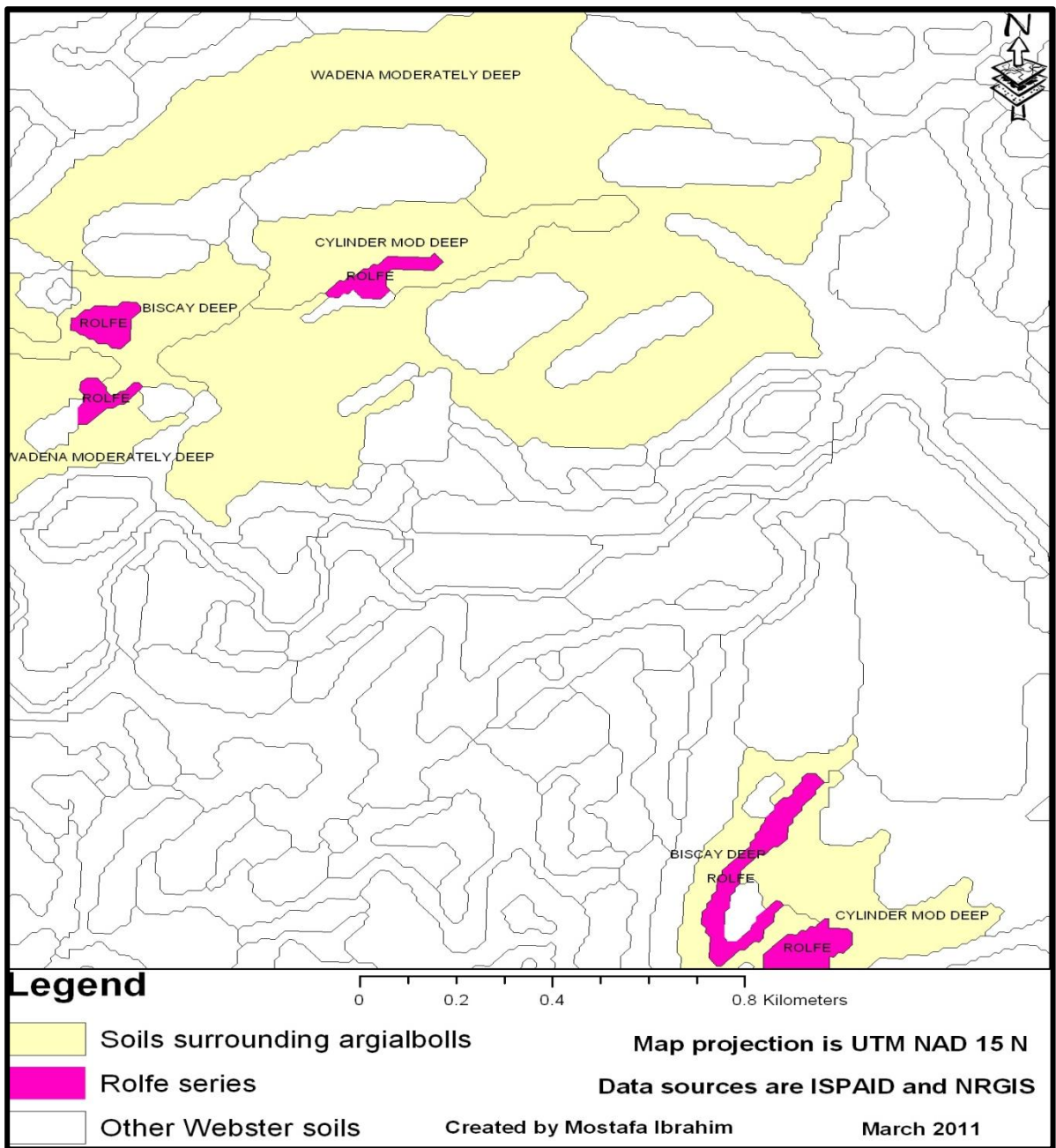


Figure 2.7. An example of Argialboll soils which are adjacent to soils formed in outwash in Webster County, Iowa.

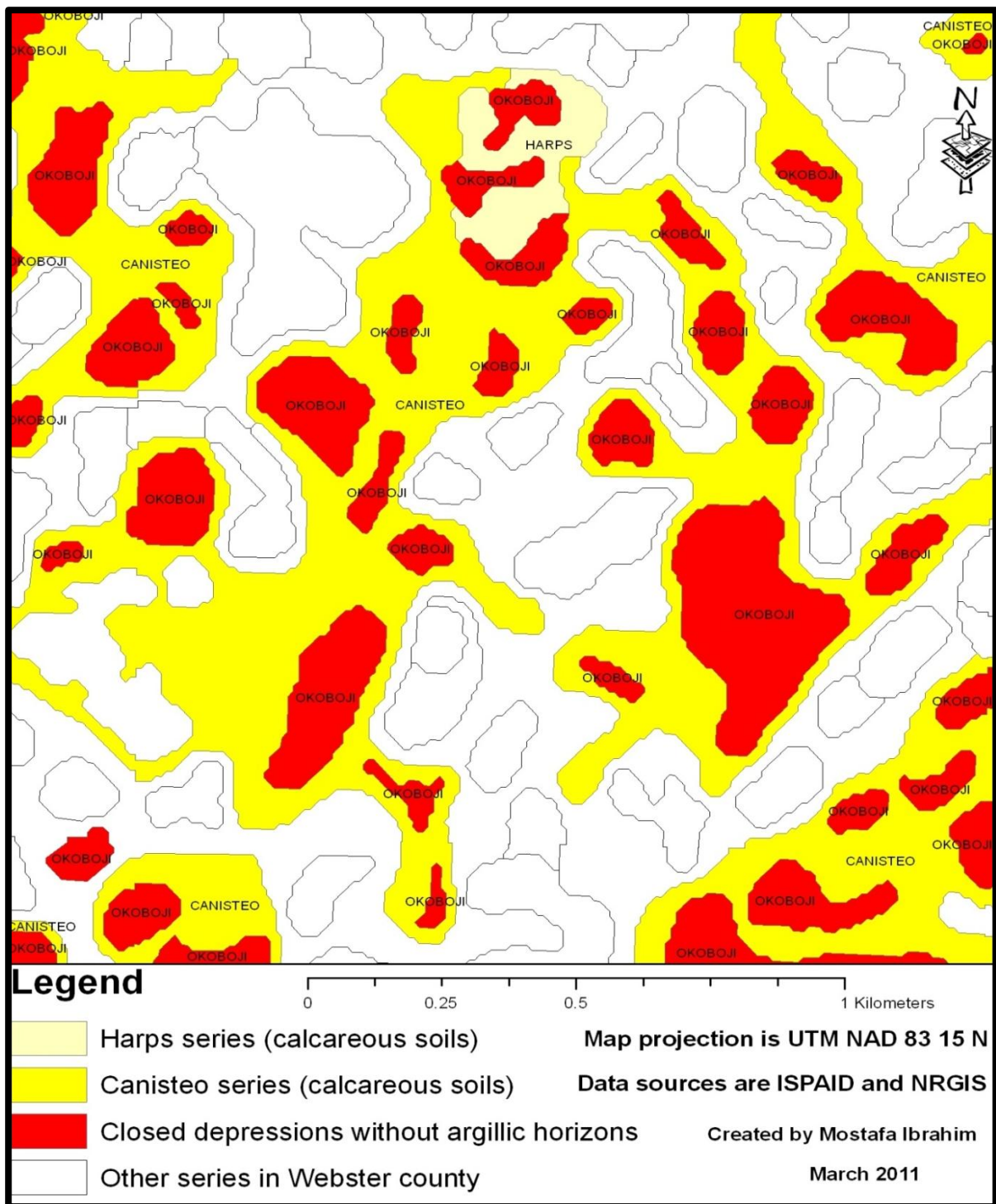


Figure 2.8. An example of closed depressions that are surrounded by calcareous soils in Webster County, Iowa.

Table 2.1. Locations and selected parameters for study counties in states around Iowa.

County number	County name	State	Latitude	Longitude	MAT [†] °C	MAP [‡] mm	Prevalent parent materials [§]	Prevalent native veg. [¶]
1	Cavalier	ND	48.81N	98.45W	2.6	474	WT	TG
2	Dickey	ND	46.14N	98.52W	5.9	508	WT	MG
3	Stutsman	ND	47.07N	98.96W	4.9	449	WT	MG
4	Brookings	SD	44.39N	96.80W	5.7	578	WT	TG
5	Day	SD	45.41N	97.62W	5.9	536	WT	MG
6	Kingsbury	SD	44.40N	97.50W	7.2	600	WT	TG
7	Miner	SD	44.03N	97.61W	7.6	542	WT	TG
8	Spink	SD	44.97N	98.38W	6.5	511	Lacustrine , WT	MG
9	Turner	SD	43.38N	97.16W	8.0	612	WT	TG
10	Lincoln	MN	44.43N	96.24W	7.3	622	WT , WL	TG
11	Otter Tail	MN	46.46N	95.69W	5.2	590	WT	TG , DF
12	Rice	MN	44.38N	93.29W	6.8	787	WT	DF,TG
13	Johnson	MO	38.79N	93.77W	13.8	981	Residual , PL	TG , DF
14	Carroll	MO	39.48N	93.55W	13.0	918	PIT , PL , shale	DF , TG
15	Clay	NE	40.53N	98.05W	10.7	698	PL	TG
16	Fillmore	NE	40.57N	97.61W	11.0	653	PL , alluvium	TG
17	Sangamon	IL	39.79N	89.68W	11.5	911	PL	TG , DF

[†] MAT (Mean Annual Temperature)

[‡] MAP (Mean Annual Precipitation)

[§] WT (Wisconsinan till), PL (Peoria loess), WL (Wisconsinan loess), PIT (Pre-Illinoian till)

[¶] TG (tall grass), MG (mixed grass), DF (deciduous forest)

County numbers refer to figure 1. Latitude and longitude are for the county center.

Table 2.2. Distribution of argillic horizons in study counties in states around Iowa.

County number	County name	State	County area (ha)	Total argillic horizons area.		Argillic horizons area			
				ha	% [†]	Mollisols		Alfisols	
						ha	% [‡]	ha	% [‡]
1	Cavalier	ND	391869	36722	9.4	33715	91.8	3007	8.19
2	Dickey	ND	295302	40837	13.8	40837	100	0.00	0.00
3	Stutsman	ND	595056	44828	7.5	44828	100	0.00	0.00
4	Brookings	SD	208388	5401	2.6	5401	100	0.00	0.00
5	Day	SD	282553	116647	41.3	116647	100	0.00	0.00
6	Kingsbury	SD	223796	65090	29.1	65090	100	0.00	0.00
7	Miner	SD	148157	46671	31.5	46671	100	0.00	0.00
8	Spink	SD	390725	118001	30.2	118001	100	0.00	0.00
9	Turner	SD	158509	9895	6.2	9895	100	0.00	0.00
10	Lincoln	MN	139861	11685	8.5	11685	100	0.00	0.00
11	Otter Tail	MN	575995	270819	47.0	107487	39.7	163332	60.31
12	Rice	MN	133588	59706	44.7	8632	14.5	51074	85.54
13	Johnson	MO	213935	157566	73.7	117724	74.7	39842	25.29
14	Carroll	MO	181703	117741	64.	95042	80.7	22699	19.28
15	Clay	NE	147631	134903	91.4	134903	100	0.00	0.00
16	Fillmore	NE	149302	139674	93.6	139674	100	0.00	0.00
17	Sangamon	IL	226932	99160	43.7	64811	65.4	34349	34.64

[†] % of total argillics is out of total area of the county.

[‡] % of argillics in Mollisols and Alfisols are out of the total area with argillic horizons.

County numbers refer to table 2.1.

Table 2.3. Argillic horizon extent in the three study counties in Iowa.

County	MAT† °C	MAP‡ mm	Prevalent parent material§	Prevalent native veg.¶	Total argillic horizons area.		Argillic horizons area			
							Mollisols		Alfisols	
					ha	%	ha	%	ha	%
Marshall	8.9	841	WL,WT	G	73036	49	66694	91	6341	9
Guthrie	9.7	775	PIT,WT,WL	G,DF	85193	55	55658	65	29535	35
Webster	8.5	875	WT	G	7732	4	3571	46	4160	54

† MAT (Mean Annual Temperature)

‡ MAP (Mean Annual Precipitation)

§ WT (Wisconsinan till), WL (Wisconsinan loess), PIT (Pre-Illinoian till)

¶ G (grass), DF (deciduous forest)

Chapter 3. Clay movement in sponges and sand columns – A pedological investigation

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Abstract

Movement of clay particles and colloids through the soil profile has been investigated extensively during the past decades. This movement has significant impacts environmentally and pedologically. The pathway of movement is generally accepted as being predominantly downward. Our hypothesis is that clay and colloid movement is multidirectional and concomitant with water movement. To test our hypothesis we conducted four demonstrations. To mimic the soil matrix, we used sponges in one demonstration, pure medium sand (250 to 500 micron diameter) in one demonstration and stratified sandy loam and sand in two demonstrations. . The first demonstration was run using sponges standing vertically in shallow aluminum pans. The second demonstration was run in pure sand columns standing in aluminum pans. The third demonstration was run in columns that had different layers of pure sand and sandy loam. The columns were set in glass beakers. The fourth demonstration was to test the likelihood of clay particles movement by diffusion. We established a water table level in the third and fourth demonstrations. In each demonstration we visually tracked movements of the clay-sized materials and used a digital camera to record what we observed. The sponge demonstration showed that water moved upward faster than the clay particles, but after 300 hours, fine and total clay suspensions had

migrated about 3 cm upwards. Sand columns demonstrations results showed that clay moved upward to a height of 15 cm in less than 24 hours. The third and fourth demonstrations results showed that clay particles can move upward and downward simultaneously as well as by diffusion.

Introduction

Soil fabric is the spatial arrangement of soil components, solids, liquids and gases (Bullock et al., 1985). The solids part is composed of organic and inorganic materials. In addition, these solids can be divided into coarse materials that are larger than 2 micron in diameter, soil skeleton and fine materials that are smaller than 2 micron in diameter, soil plasma (Brewer and Sleeman, 1988). Soil plasma consists of the components of soil materials that are capable of moving, such as inorganic or organic clay particles. These particles are also known as soil nanoparticles (Schaetzl and Anderson, 2005; Kretzschmar and Schäfer 2005).

Movement of clay particles has been investigated extensively through the past decades for different interests. This movement is important environmentally because heavy metals, pesticides, or fertilizers can be translocated to the ground water and contaminate it via their adsorption on mobile clay particles (Ryan et al., 1998; Sprague et al., 2000). This movement is also important pedologically because formation of some soil diagnostic horizons, such as the albic, argillic and spodic horizons, is concomitant with clay particle movement (Soil Survey Staff, 1999). McKeague and St. Arnaud (1969) and Dixit (1978) stated that clay particles can move downward from the upper horizons and deposit in the

lower horizons. The process of clay particles translocation in suspension downwards is known as lessivage (Schaetzl and Anderson, 2005).

In fact, many researchers did a lot of work to prove the likelihood of downward movement of these particles either in saturated or unsaturated conditions. For example, Pilgrim and Huff (1983) and El-Farhan and others (2000) found that clay particles and colloids can move in the liquid medium through soil pores during infiltration events. They also reported that this movement is controlled by the flow rate and chemistry of porewater and the soil moisture content. Rousseau and others (2004) demonstrated the downward movement using undisturbed soil columns in the laboratory.

Factors affecting clay movement were suggested by different researchers. Zhuang and others (2007) and Sharma and others (2008) attributed the colloidal movement in soils to the moving air–water interface. Michel and others (2010) suggested that colloid movement is affected by gravitational water drainage, water evaporation from the soil and water profile redistribution from preferential flow paths toward the soil pores.

All of the literature discussed assumed the likelihood of downward movement of clay particles. They assessed this movement as well as investigating the factors that have impacts on it. Thus, they have always supplied liquids from the top of their soil columns. We do not know any researcher who tried to test the upward movement of these particles.

The aim of this paper is to investigate whether unsaturated flow can result in upward movement, of clay particles and evaluate the pedological ramifications of multidirectional clay migration.

Materials and methods

Preparation of clay suspension

In order to obtain clay-sized material for this demonstration, about 2 kg from a reddish paleosol soil (a Yarmouth-Sangamon paleosol collected from the Montour Quarry (42° 01' 21" N latitude, 92° 43' 54" W longitude) owned by Wendling Quarries, Inc., located in Tama County, Iowa) was placed in several 1000-ml beakers and ultimately fractionated into clay, silt and sand fractions. Each beaker contained approximately 200 g of soil. Distilled water was added to the contents of each beaker until soils became saturated and then approximately 100 ml of 1% glacial acetic acid were added to remove CaCO_3 . Organic matter was removed by adding 30% hydrogen peroxide (H_2O_2) gradually until foaming disappeared. The beakers were placed on a electric hotplate at a low temperature to accelerate the reactions. Next, we removed all excess cations in the sample solution by washing with distilled water, which included leaving them overnight and then decanting the supernatant. We repeated this step until the contents became partially suspended. Afterwards, soil samples were quantitatively transferred to plastic bottles. To each bottle a 200 ml aliquot of the dispersing agent (35.7 g of sodium hexametaphosphate and 7.94 g of Na_2CO_3 were dissolved in 1L distilled water) was added. The bottles were then shaken overnight (Soil Survey Staff, 2004).

Silt and clay fractions were separated from the sand fraction by moist sieving. The sand on the sieve was discarded. The silt and clay suspension that passed through the sieve was collected in 20 L containers. The clay fraction (<2 micron) was separated via siphoning from the silt fraction using Stokes' Law to determine when all silt had fallen below the depth

of siphoning. The entire clay fraction was removed via repeated siphonings, with each siphoning following thorough agitation of the remaining silt-clay suspension. Four liters of the total clay suspension were further fractionated into fine (<0.2 micron) and coarse clay (0.2 to 2.0 micron) fractions using the centrifuge method of Jackson (1985). In particular, Equation 3-7 was used to calculate centrifugation time (Jackson, 1985). The total clay suspension properties were 14.2 g L^{-1} total clay concentration, 7.3 pH and 0.044 Sm^{-1} EC. The fine clay suspension had 12 g L^{-1} concentration, 7.3 pH and 0.03 Sm^{-1} EC. The coarse clay suspension had 2.8 g L^{-1} concentration, 6.8 pH and 0.003 Sm^{-1} EC. It is important to remark the clay suspension had a reddish color which enabled us to visually track it in our demonstrations. We attribute the reddish color to the occurrence of iron oxide coatings on clay surfaces.

Demonstration design

Our work was carried out as four demonstrations, which were developed and implemented sequentially. The first demonstration was to simply intended to test whether upward movement of a clay suspension occurs as part of capillary rise in a sponge. The second demonstration was conducted in sand columns to test the same idea with a more soil-like matrix. The silicate sand was medium sized (i.e., primarily 250 to 500 micron in diameter). It was obtained from UNIMIN Corporation (2011). We evaluated the purity of quartz in the sand by visual inspection, including hands lens and by testing for carbonate minerals by adding drops of 10% acetic acid. Prior to our using the sand, we washed it with distilled water and then dried out in the oven at 100°C . The size of the sand was determined using dry sieving (Soil Survey Staff, 2004).

The third demonstration was designed to determine the directions clay particles can move. It was carried out in two steps. The first step was conducted in columns wherein a 4 cm thick layer of sandy loam was placed between two zones of pure sand – each about 5 cm thick. The second step was conducted with four strata. One was a 5 cm thick strata of sandy loam. The other three strata were pure sand. The sandy loam was created by mixing about 81% medium quartz sand with 19% clay that had been fractionated from the aforementioned paleosol sample. The clay fraction was obtained from the dry clay crusts formed in the aluminum pans in the first and second demonstrations, after they dried out. Then, these clay crusts were ground using an electrical grinding machine (Retsch grinding machine). The fourth demonstration was conducted with a 3 cm sandy loam layer and two layers of pure sand to test the possibility of clay movement by diffusion and/or capillarity.

For the first demonstration, we stood upright a single clean and dry sponge (7 AU utility cellulose sponge 15.9 x 10.5 x 4.1 cm; Glit Microtron, 2011) in each of six dry, clean aluminum pans. Each pan was 20 cm in diameter (Figure 3.1). All of the sponges were marked at a depth of 2 cm from the bottom to identify the initial clay suspension level to be added to the aluminum pans. We poured total clay suspension in four pans until it reached the marked line on the sponges. Immediately, we photographed each sponge using a digital camera to show the starting point of both water and clay. The same process was performed on two more sponges, one for the coarse clay and one for the fine clay. We kept the clay suspension level constant in the pans during the demonstration time.

We periodically photographed each sponge in order to track the movement of the water and clay. All of the pictures were downloaded to the computer. For ease of viewing,

each photograph was added as a slide to the Microsoft Power Point software. Next, these pictures were printed out. Total height of each sponge and both water and clay heights on each sponge were measured on the printed photographs using a ruler. We calculated the real height of water and clay on sponges by using the formula: total height of sponge in the picture / total height of sponge in reality = clay height in the picture / clay height in reality. The same formula was used to calculate water heights. For each sponge, total height of sponges in reality is known, total height of sponges in the pictures was measured and heights of both water and clay in pictures were measured. The only unknown variable is water or clay height in reality that can be calculated from the formula above.

For the second demonstration (i.e., water and clay movement in pure sand columns), twelve sand columns were used. Ten of them were for total clay, one for fine clay and one for coarse clay. Five sand columns of the ten used for total clay had a constant water table and the other five were exposed to wetting and drying cycles. We used clean, transparent plastic bottles with two to five mm diameter holes in their bottoms as containers for the sand columns. Each of the columns was 7 cm in diameter and 15 cm in height. Bluntly each of these containers was originally a 24-oz plastic soda bottle that had its top cut off and had been thoroughly washed. The holes in the bottom were cut using a knife. Each cylinder was stood empty in a dry, clean aluminum pan and then filled with clean and dry medium quartz sand (Figures 3.2 and 3.3). The bulk density of the sand was 1.74 gcm^{-3} and the total porosity was 34.3%; assuming that the particle density of sand is 2.65 gcm^{-3} . Next, we supplied total, fine and coarse clay suspensions slowly at the base of each pan until reaching the marked line

at 2 cm at the bottom of the sand columns. The movement of clay suspension in all sand columns was tracked by using a digital camera.

In the third demonstration (layered sand and sandy loam), we tested how clay particles behave in unsaturated conditions. Two columns were used. We installed two transparent plastic bottles that had holes at their bottoms in two 500 ml glass beakers. For the first column, we filled a depth of 9 cm with clean, dry and pure medium sand. Next, we slowly added water to the beaker walls so that water got into the sand column from the bottom and then moved upwards by capillarity. We kept adding water to the beaker wall until water height became the same inside the sand column and outside it – i.e., in the beaker. This height of water was the water table. Then, we added a 4 cm layer of a dry sandy loam immediately above the saturated sand (first three columns of Figure 3.4). We sought to add the sandy loam layer in a dry state because we wanted to inhibit the downward movement of clay which occurs in the sandy loam layer, at this time. However, water from the established water table moved upward as capillary fringe until it reached the top of the sandy loam layer. We kept supplying water in the beaker to keep the water table at the same level immediately before time zero. Next, we added a 3 cm layer of nearly saturated, clean and pure sand in order to inhibit the upward movement of clay from the sandy loam layer. In the second column, we disconnected the sandy loam layer from the water table by adding a 4 cm layer of pure sand between them (first three columns of Figure 3.5).

The fourth demonstration was to investigate if clay could move between sand layers by diffusion. We conducted this demonstration as two steps. First, we used one sand column from demonstration number two because it had deposited clay particles in it. Next, we put it

in an empty glass beaker; and then we added water to the beaker so that this water could move upward inside the sand column (Figure 3.7). Second, we put a transparent and clean plastic bottle in a glass beaker and filled it with dry, clean and pure sand to a 12 cm depth. Next, we added distilled water to the beaker to a 7 cm depth from the bottom in order to establish the water table at this level. We added a 3 cm layer of dry sandy loam. Next, we added a 2 cm layer of dry, clean and pure sand (the first four columns of Figure 3.8). We meant to maintain all of the layers above the water table in a dry condition as long as possible in order to assure upward movement of water and to inhibit downward movement of clay at time zero. Movement of clay was tracked using a digital camera.

Results and discussion

Sponge demonstration

To investigate the potential for upward movement of a clay suspension we initially used sponges. The use of sponges was simply as a rough, first approximation of a soil. This is analogous to what many soil science courses do as they demonstrate water behavior. In the first five minutes after the clay suspension was added to each sponge, upward migration of water and clay occurred at the same rate (Table 3.1; Figures 3.9 and 3.10). After 10 minutes, the rate of upward movement of water exceeded clay; i.e., pure water was separating away from the clay suspension. After 75 hours, the sponges were entirely moist (Table 3.1). Total and fine clay upward migration remained slow during the first 200 hours (Figures 3.9 and 3.10). Then between 200 and about 300 hours there was more noticeable upward migration of fine clay and total clay. That is, it restarted and then finally stopped.

We interpret the movement of clay particles between 200 and 300 h as a series of pulses wherein the initial migration of clay occurred as the first pulse of water was pulled up by simple capillarity. With time the sponge began drying, which caused the pores to shrink. That shrinkage promoted a subsequent round of water and clay migration upward (Figures 3.9 and 3.10). After 300 hours, the clay seemed to permanently stop moving upwards because either the pores got plugged by the clay accumulation process or an equilibrium was reached between water, clay and the smallest pore sizes that ever occurs in the sponge.

Coarse clay migration was less apparent. Based on this and the behavior of the fine clay we speculate that the sponges having total clay acted analogous to the stationary phase in chromatography, separating the fine and coarse clay with the fine clay migrating upward. At the beginning of the demonstration, coarse clay moved to a 1.1 cm height and then stopped through the whole period of the demonstration. Figure 3.10 shows that at the beginning of the demonstration all of total, fine and coarse clay moved upwards at almost similar rate.

During the demonstration, we noticed that the dark color - which represents clay particles on sponges – would appear at a specific height as a light color at first and then progressively get darker and darker. Once it was dark, the same cycle would take place again at a higher point and subsequently a higher point until it finally reached the maximum height (3.1 cm, Table 3.1). We interpret this as more and more clay would accumulate at a point over time.

Sand columns demonstrations

After observing that clay did spontaneously migrate upward in sponges, we decided to test if it could occur in sand columns. Thus, we installed demonstration number two . When we supplied clay suspension to the aluminum pan to the height of 2 cm at the bottom of the sand columns, some of the clay suspension rapidly moved upwards inside the sand column (Figure 3.3). After 4 h and 20 min., the top of the sand columns became wet; however, there was no reddish color that we used to indicate clay, appeared. The clay particles only started to appear at the top of all of the sand columns that have total and fine clay suspension at their bases, after about 22 hours. However, the coarse clay started to appear at the top of its sand column after four days.

Frustratingly, we could not consistently see the water and clay suspension dynamics as clearly as we could with sponges. The exception is we could observe with high certainty what occurred at the top of the columns (Figure 3.11). Figure 3.6 also clearly exhibits what occurred although we must note it is a column we set up to beta test our protocol – and we did not record the timing of water and clay movement. Returning to the sand columns of demonstration number two, clay continued to move upwards and accumulate at the top of the columns creating a darker color day after day (Figure 3.11). There was no difference in color of the deposited clay particles between the set of columns that have a constant water table and the other set that was exposed to wetting and drying cycles (Figure 3.11).

Extending our idea to field settings we think that, as water infiltrates the upper sola during a rainfall event, water could carry clay particles downward. However, after the rainfall stops, we think clay movement can be in any direction – with non-gravitational water pulling clay around. Clay migrates whichever way the water is redistributed within soil profile. We

think this explanation is consistent with oriented clay films along vertical pore walls and – most tellingly – along horizontal pore walls.

Given that with natural conditions soils have water tables, we ran a third demonstration to better mimic field conditions. We used two different columns. The first sand column had two layers of clean sand sandwiching a layer of sandy loam (Figure 3.4). The other column had an additional pure sand layer separating the sandy loam layer from the water table (Figure 3.5).

In the column with three layers (i.e., first column of demonstration three) we added the upper layer as nearly saturated clean and pure sand. This was to resemble the soil surface conditions immediately after a rainfall event stops. The first kind of water to be lost from this layer (naturally, the thickness of this layer depends on the intensity of the rainfall event as well as soil matrix composition) is the gravitational water that moved downward through the underlying sandy loam layer carrying with it clay particles from the sandy loam layer to the bottom of the glass beaker (Figure 3.4). This downward movement continued for 14 hours, although the amount of gravitational water was not much. After 14 hours, clay particles started to move upward from the sandy loam layer to the upper sand layer. We attribute this upward movement to the dryness of the column surface causing water to move from wetter positions to drier ones. In other words, water was moving from high total potential head to lower total potential. This upward movement continued until clay reached the top of the sand column and accumulated on after 88 hours. It is useful to note that as an independent preliminary trial of this step, clays continued to accumulate at the top of the sand column as long as water table existed (Figure 3.6).

In the four layers column (i.e., the second column of demonstration three), we added the upper layer in a dry condition. Once water moved from the water table and reached about two-thirds of the sandy loam layer thickness, we started to supply drops of water slowly at the top of the sand column. When water moves upward or downward through soil pores, it displaces soil air. In this sand column, water was moving upward coming from the water table and we supplied water at the top; consequently, the entrapped air between the two water surfaces had to go somewhere. As a result, the entrapped air created cracks in this sand column (Figure 3.5). This observation agrees with what was stated by Jarrett and Fritton (1978), Suhr and others (1984) and Wang and others (1998) where they attributed the formation of some cracks within the soil solum to the high pressure produced by the entrapped air.

We stopped adding water at the top of this sand column once the upward and downward moving waters met. Afterwards, the common direction of water movement became downward carrying with it clay particles. This clay downward movement continued through the sand layer occurring below the sandy loam layer until it reached the water table. After two hours, clay movement became obvious (Figure 3.5). After 22 hours, clay continued to move downward only and accumulate at the bottom of the beaker outside the sand column. At 49 hours, clay upward movement became apparent (Figure 3.5). It is important to notice the occurrence of clay movement in both directions, downward and upward, was at the same time after 49 hours. We could tell this because clay accumulation was continuous at the bottom of the beaker while simultaneously it continued with upward movement. As a result of this observation, we designed the fourth step to further our understanding of clay

movement – which we think is a combination of diffusion, capillary flow and gravitational flow - in sand columns.

In the fourth demonstration, we were testing the likelihood of clay movement by diffusion. One of the sand columns of demonstration number two was used after we cleaned it. We chose to use one of sand columns of demonstration two because all of them had clay inside them (Figure 3.7). After three hours, clay started to get out of the bottle to the water in the beaker and continued to accumulate throughout the water in the beaker.

To make sure that clay movement took place by diffusion, we installed the other sand column of demonstration four (Figure 3.8). This sand column had two sand layers sandwiching a sandy loam layer. All of the sand and sandy loam layers were set in a dry state. We supplied water to the glass beaker so that it would get into the sand column from the bottom and move upwards only. We kept adding water to the beaker to preserve the water table. Once water reached the top of the sandy loam layer and started to move through the upper pure sand layer, clay particles started immediately to move upward from the sandy loam layer to the upper sand layer. The upward movement of clay particles continued for four hours until it reached the top of the column; at this time we did not observe any clay particles at the bottom of the beaker. In other words, we did not observe any downward movement of clay particles. At the sixth hour, we noticed clay particles at the bottom of the glass beaker which means the downward movement was taking place before the sixth hour. Although the water table was low and water movement should be upward only, clay particles moved downward. We attribute this downward movement to the movement of clay from

positions with higher clay concentration to positions with lower clay concentration through water and gravitational flow.

Pedological ramifications

Our results demonstrate that clay particles can move upwards and even accumulate on the soil surface, at least in sand columns in the laboratory. We think this is important and will ultimately need to be considered as all pedologists continue to refine our understanding of clay migration and horizonation. For example, our data can be extended into soil formation scenarios of some well-known morphologic features such as lamellae, albic and argillic horizons.

Lamellae

Lamellae are horizontal bands of accumulated layer silicate clays and iron oxide. They form in sandy soils formed in outwash or aeolian sand and they usually form below the solum (Gray et al., 1976; Ahlbrandt and Freyberger, 1980; Larsen and Schuldenrein, 1990; Prusinkiewicz et al., 1998; Rawling, 2000; Holliday and Rawling, 2006). Different scenarios of lamellae formation have been suggested by many researchers. It might be a result of sedimentation event or a pedogenic process like clay translocation from upper horizons to lower ones (Dijkerman et al., 1967).

Based on our results, we hypothesize that the upward movement of water is potentially responsible for forming some types of lamellae. According to our results, clay can move upwards and accumulate in a sandy matrix via unsaturated flow. Thus, over thousands of years, it seems pedogenically possible to form clayey bands that progressively thicker and

thicker and result in lamellae. We also expect that areas that have deeper water tables have deeper lamellae. Areas that have higher water table have shallower lamellae.

On the other hand, our hypothesis might contradict the hypothesis of lamellae formation by clay translocation from the upper soil layers to the lower soil layers. If lamellae formed by the clay downward translocation, it would be surprising to consistently find them in horizontal bands because mobile clay particles follow the water pathways; and in most soils from loamy to clayey soils, water flow pathways are highly irregular (Beven and Germann, 1982; Bouma, 1991). Even in structureless sandy soils, water front may split into fingers (Hillel, 1987). Consequently, translocated clay particles will not form horizontal bands but rather it will form irregular boundaries.

Albic (E) and argillic horizons

During a rainfall event, water infiltrates the soil surface, moving downward. Once the upper thickness of the soil surface gets saturated, water will start to run off in addition to its movement downward. This downward movement enhances the dispersed clay particles to move downward following water flow pathways. After the rainfall event stops, water will continue to move downward from moist positions to dry positions. This movement draws clay particles with it.

Simultaneously, water will start to be lost from the upper thickness of the soil surface by evapotranspiration. Consequently, water in the upper part of the upper horizon will move upward instead of downward. This upward movement could pull clay particles to upper positions. That means there is a zone within that horizon that loses water and clay particles in

both directions simultaneously – i.e., the albic (E) horizon. We speculate that the downward movement has a stronger effect than the upward movement because this movement takes place twice; once during the rainfall event and the second takes place as a result of water potential after the rainfall event stops. Upward movement of clay likely takes place with evapotranspiration causing upward unsaturated flow. If this is correct it is likely the 1 to 3 cm thick zone immediately above the A E horizon boundary is enriched in fine clay.

In sum, repeated downward movement of water and clay particles through hundreds or thousands of years forms the argillic horizon and helps in forming the albic (E) horizon. However, upward movement is also potentially important in both types of horizons.

Conclusions

Clay particles can move in both directions, downward and upward, following the water flow pathways. The upward movement was used to introduce a novel explanation of lamellae formation. Both downward and upward movements were used to explain the formation of both albic (E) and argillic horizons. Clay particles can move during unsaturated water flow, presumably by diffusion and capillarity.

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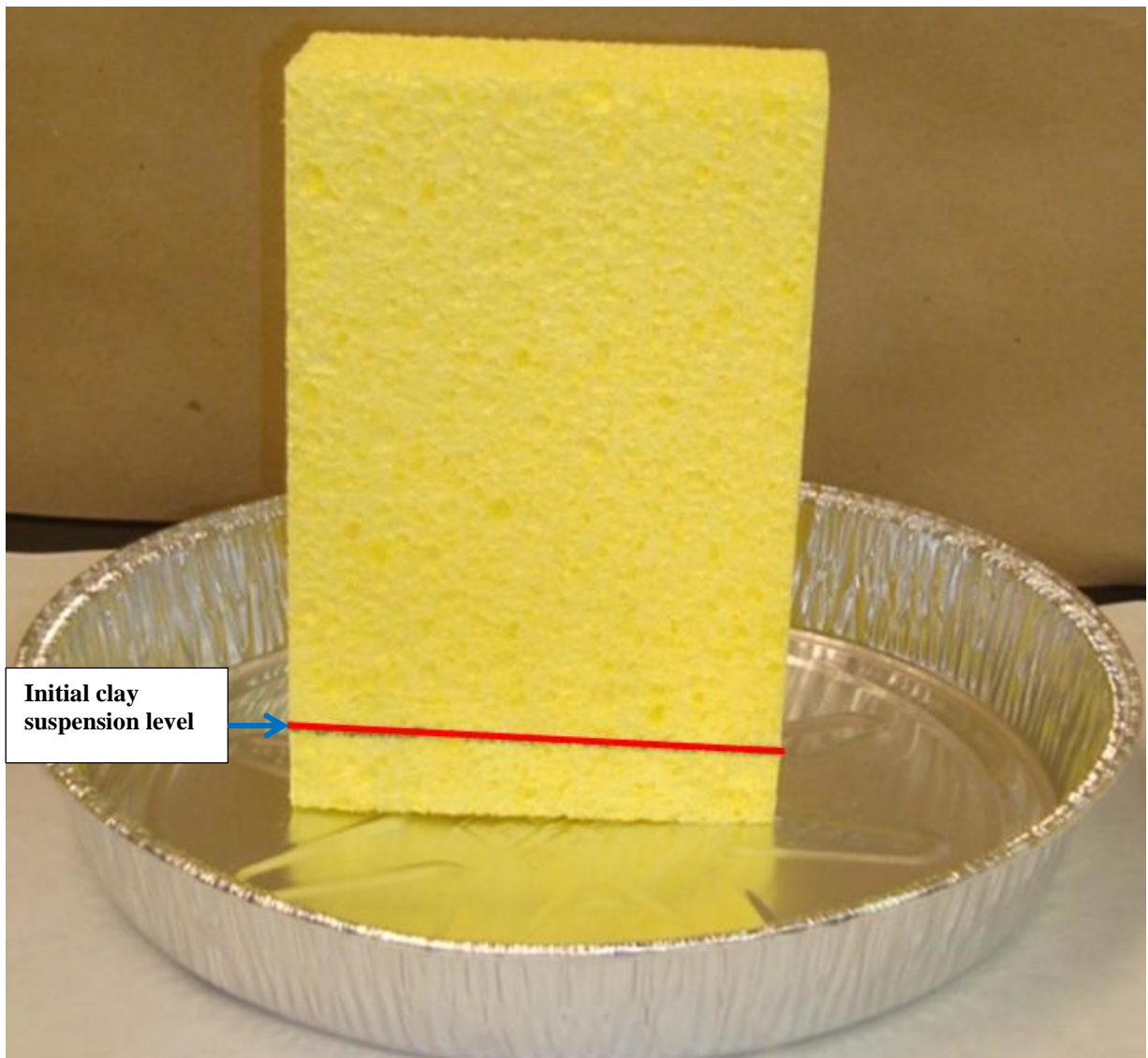


Figure 3.1. An example of the initial sponge demonstration installation.



Figure 3.2: An example of the initial sand column used in the water and clay upward movement in sand columns demonstration. The line near the base of the column was drawn there as a reference line.

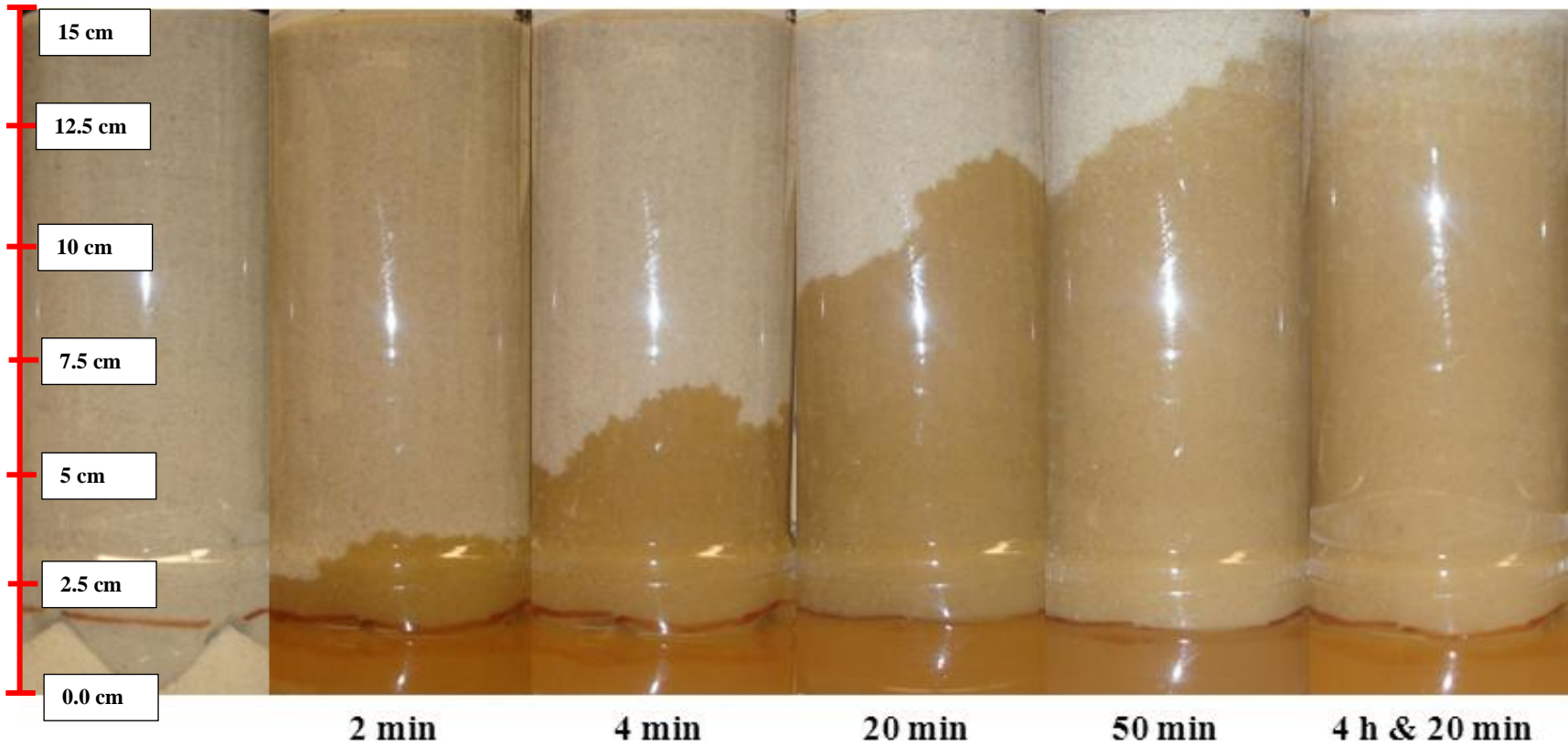


Figure 3.3. Example of clay suspension movement in pure sand columns (demonstration 2). The line near the base of each column is a reference line we added.

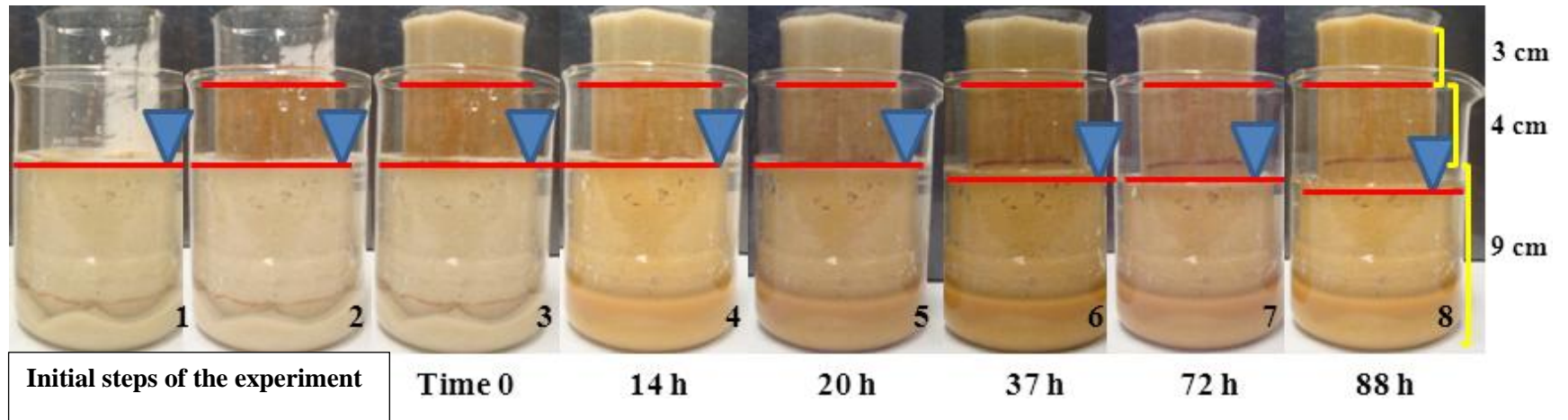


Figure 3.4. Clay particles movement in the layered sand and sandy loam columns with a direct contact between the sandy loam layer and water table.

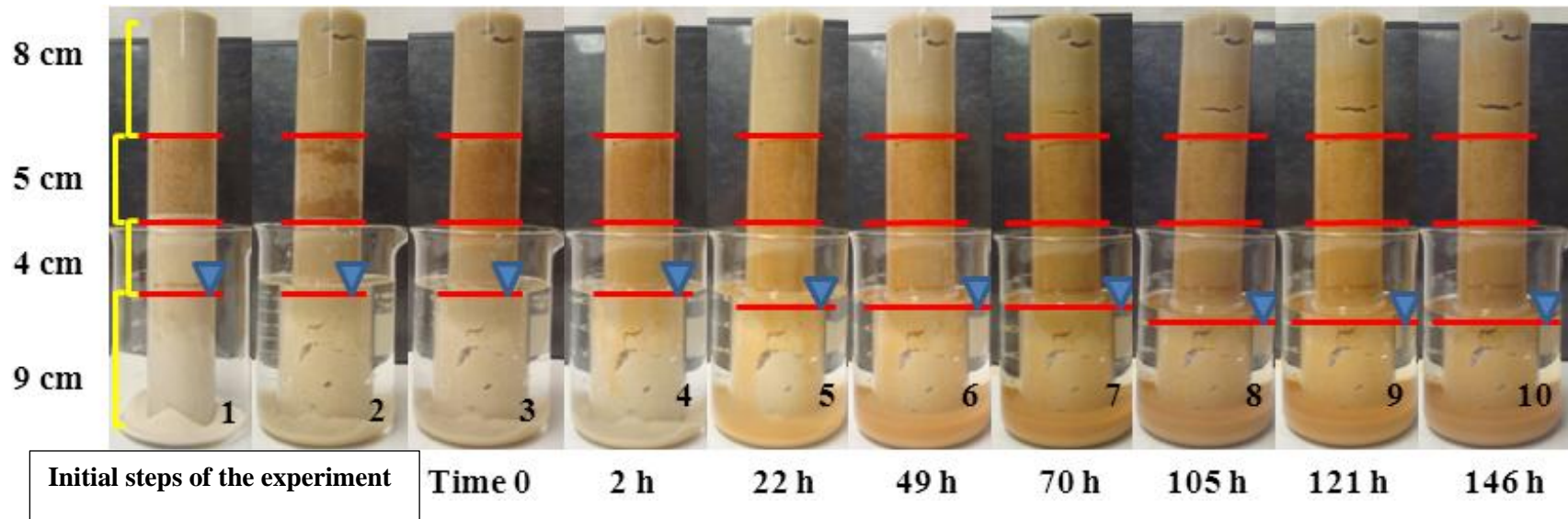


Figure 3.5. Clay particles movement in the four layers of sand and sandy clay mixture columns with an indirect contact between sandy loam layer and water table.

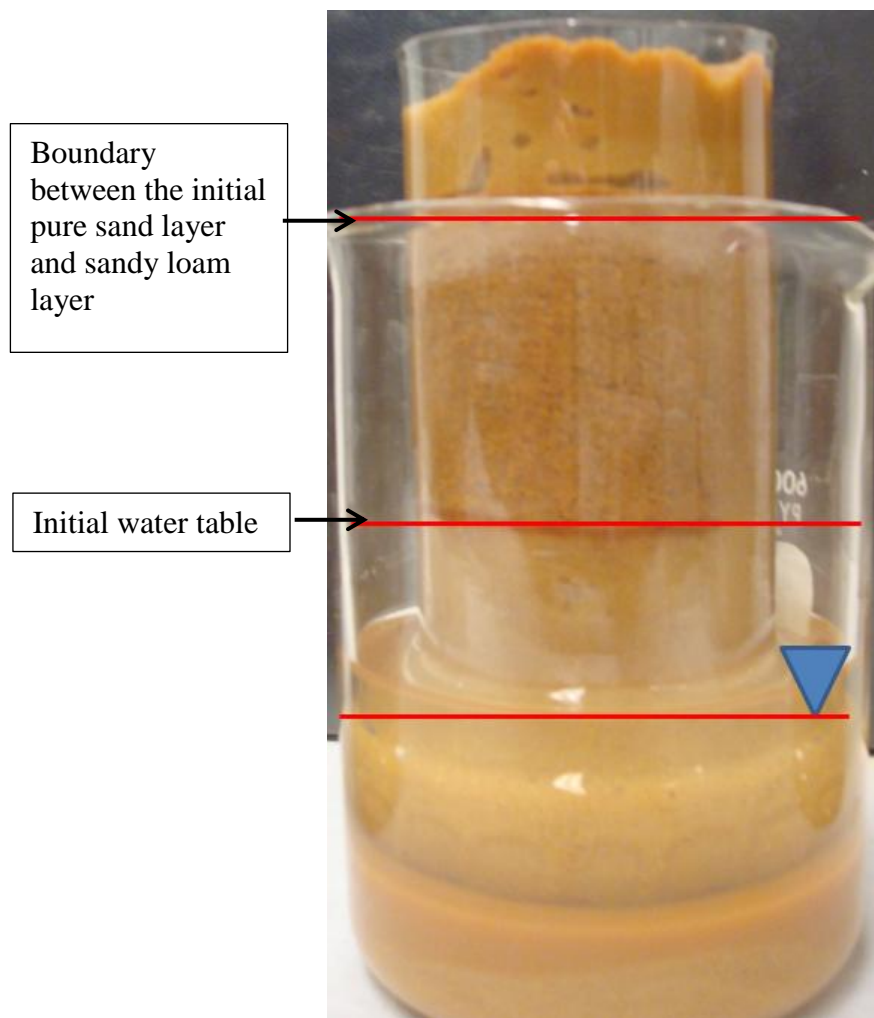


Figure 3.6. A pretrial demonstration to test clay movement behavior in unsaturated conditions.

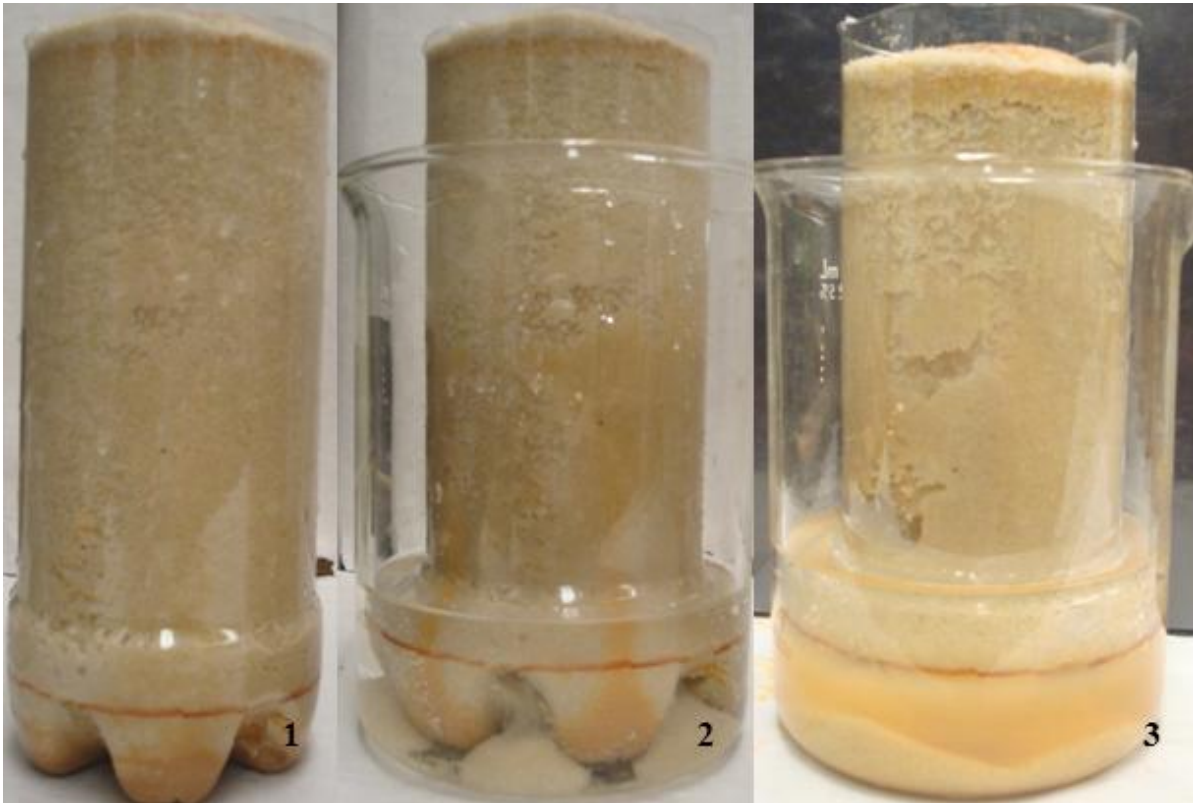


Figure 3.7. Three sequential photographs of a sand column from demonstration 2 used in demonstration 4 to test clay movement by diffusion. Please note the cloudy water in the beaker at time 3, which is evidence of clay migrating out downward of the sand column.

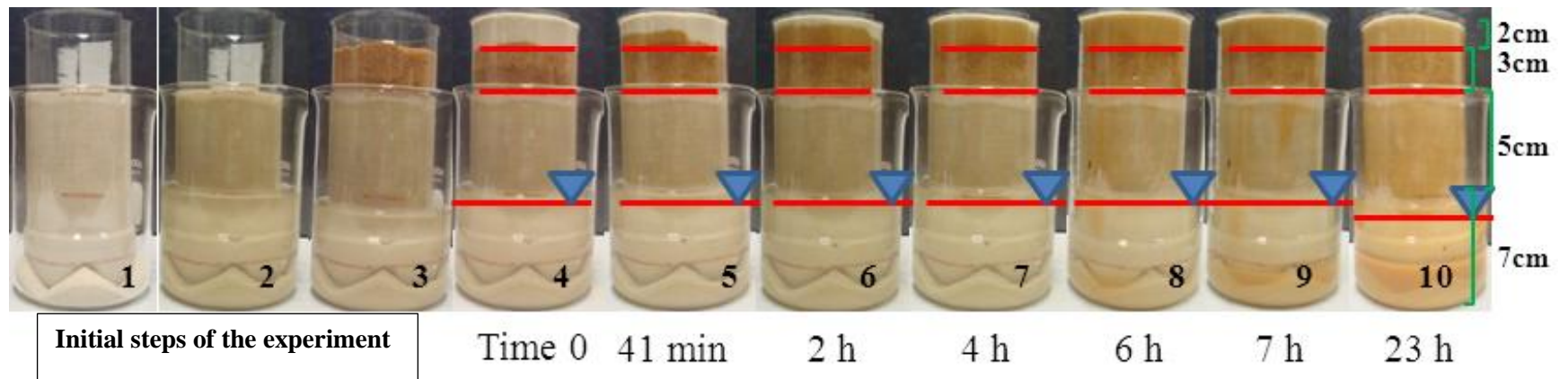


Figure 3.8. A demonstration that shows the likelihood of clay movement by a mix of diffusion, gravitational flow and capillarity flow.

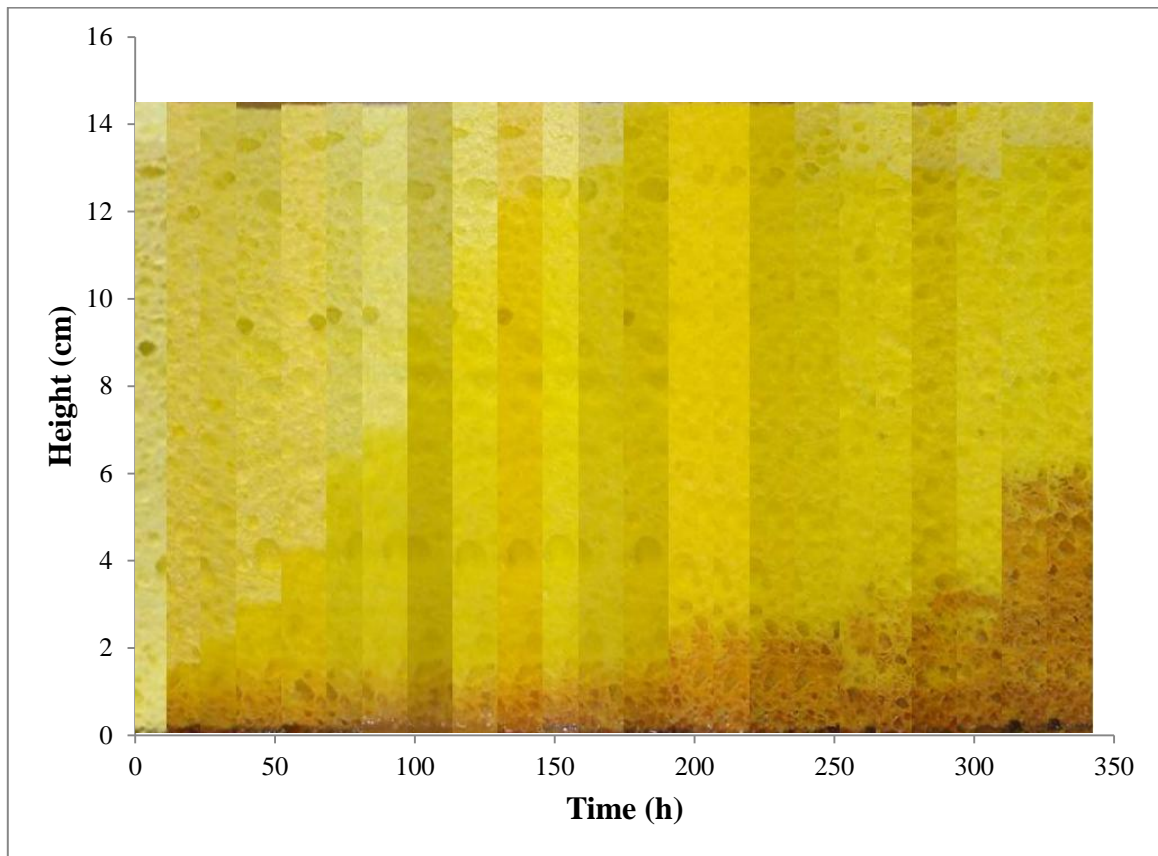


Figure 3.9. An example of water and total clay upward movement in sponges through demonstration time.

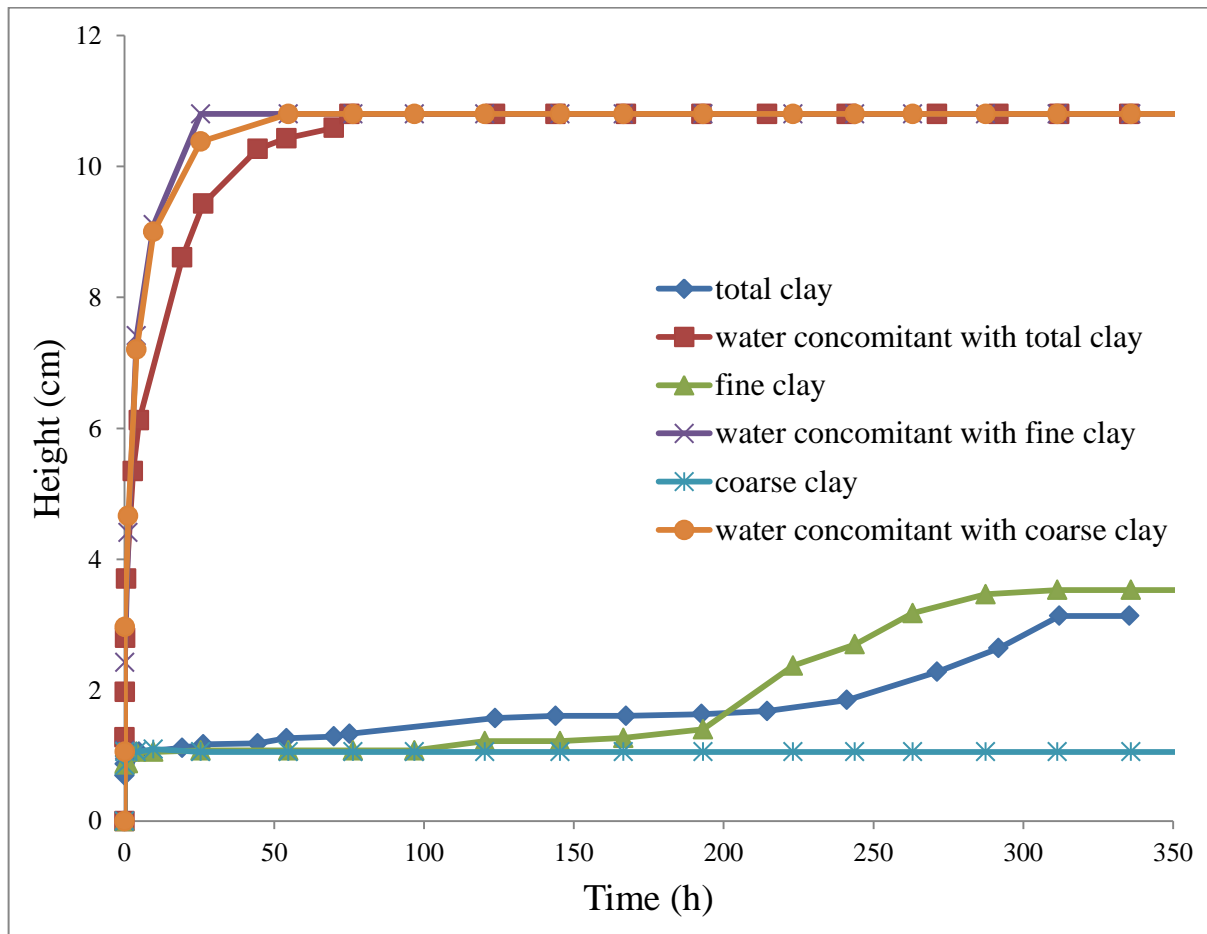


Figure 3.10. Average of total clay, fine clay & coarse clay and their accompanied water upward movement in sponges through the demonstration time.

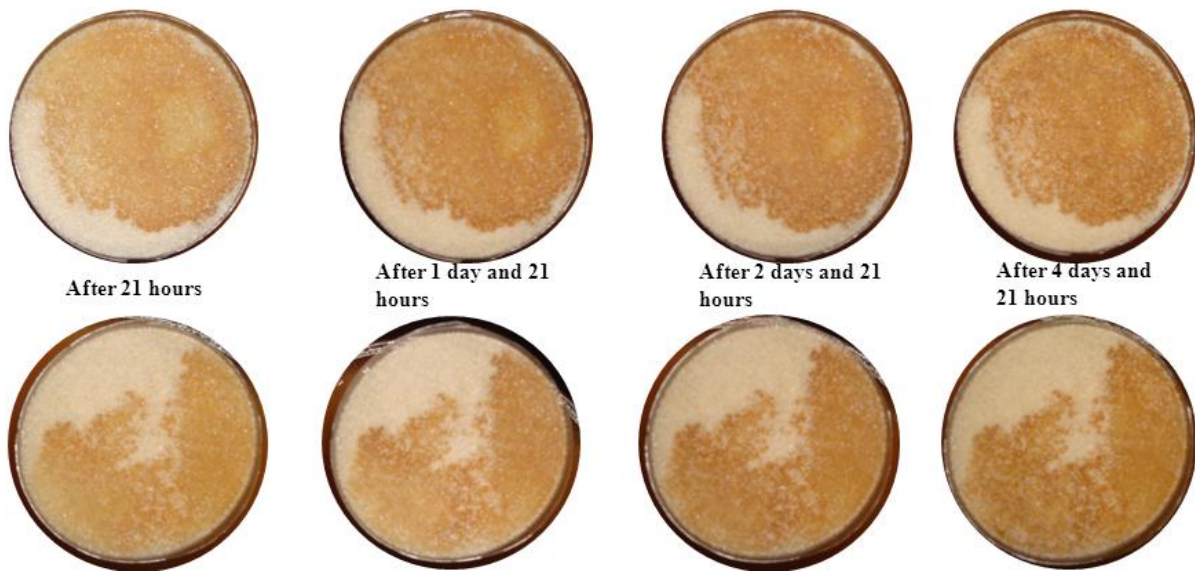


Figure 3.11. Clay accumulation at the top of sand columns in demonstration 2. The upper row of columns had their base continually in a 2-cm deep pool of clay suspension. The lower row of columns was subjected to a series wetting and drying cycles.

Table 3.1. Total clay and water heights on sponges through the demonstration time.

Sponge time (h)	Water height in sponge (cm)				Average (cm)	Clay height in sponge (cm)				Average (cm)
	1	2	3	4		1	2	3	4	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.03	1.35	1.54	1.26	0.96	1.28	0.81	0.51	0.75	0.72	0.70
0.15	1.54	2.48	1.80	2.07	1.97	0.88	0.79	0.90	0.92	0.87
0.25	2.25	3.26	2.70	2.99	2.80	1.13	0.82	1.13	0.92	1.00
0.58	2.93	4.54	3.60	3.76	3.70	1.13	0.86	1.13	0.94	1.01
2.85	4.73	5.62	5.18	5.87	5.35	1.13	0.86	1.13	0.94	1.01
4.90	5.18	7.20	6.08	6.05	6.12	1.13	0.90	1.13	1.08	1.06
19.3	7.71	9.94	8.16	8.64	8.61	1.21	0.97	1.21	1.08	1.12
26.3	8.38	10.8	9.26	9.29	9.43	1.21	0.97	1.21	1.30	1.17
44.4	9.11	10.8	10.4	10.8	10.3	1.27	0.97	1.21	1.30	1.19
54.1	9.53	10.8	10.6	10.8	10.4	1.27	0.97	1.30	1.53	1.27
69.9	9.95	10.8	10.8	10.8	10.6	1.27	0.97	1.30	1.63	1.29
75.2	10.8	10.8	10.8	10.8	10.8	1.27	0.97	1.30	1.80	1.33
124	10.8	10.8	10.8	10.8	10.8	2.04	0.97	1.48	1.80	1.57
144	10.8	10.8	10.8	10.8	10.8	2.04	0.97	1.48	1.94	1.61
168	10.8	10.8	10.8	10.8	10.8	2.04	0.97	1.48	1.94	1.61
193	10.8	10.8	10.8	10.8	10.8	2.04	0.97	1.59	1.94	1.64
215	10.8	10.8	10.8	10.8	10.8	2.16	1.03	1.59	1.94	1.68
241	10.8	10.8	10.8	10.8	10.8	2.59	1.14	1.73	1.94	1.85
271	10.8	10.8	10.8	10.8	10.8	2.59	1.17	2.33	3.02	2.28
292	10.8	10.8	10.8	10.8	10.8	2.59	2.36	2.59	3.02	2.64
312	10.8	10.8	10.8	10.8	10.8	4.28	2.54	2.70	3.02	3.14
336	10.8	10.8	10.8	10.8	10.8	4.28	2.54	2.70	3.02	3.14

Chapter 4. Munterville - reinterpreting the genesis and classification of pedons with shale in their sola from MLRA 108 and 109

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Abstract

MLRA-scale remapping of older soil map units is a useful way to evaluate changes in them, whether those changes are due to natural pedogenesis, human-induced impacts, map unit refinements or, simply, concept-induced. In 2009, NRCS-Iowa and Iowa State University collaborated in a project to remap Gosport soil map units. NRCS staff initiated this project when they noticed plant roots and argillans deep within the B horizon of Gosport (a fine, illitic, mesic Oxyaquic Dystrudept) polypedons while updating MLRA 108 and 109. They used both map unit transects and the relev   method to identify pedons for detailed laboratory analyses. The aim of this work is to classify the study pedons and investigate their pedogenesis. One representative pedon came from each of eight counties in southern Iowa – Mahaska, Monroe, Davis, Jefferson, Van Buren, Keokuk, Lucas and Marion. The results revealed a need to take some Gosport map units and remap them as the new series, Munterville, (fine, mixed, active, mesic Oxyaquic Hapludalf.) Examination of the Munterville pedons reveal some an Ultisol – i.e., a fine, mixed/kaolinitic, active, mesic Oxyaquic Hapludults – which occur whenever very acid shale is found in the control section.

Introduction

Pennsylvanian shale is extensive across southern Iowa, although most is buried under the various Pre-Illinoian drifts, Illinoian drifts and Peoria Loess that comprise the modern

Southern Iowa Drift Plain (SIDP) (Prior, 1991; Horick, 1974; Hallberg and Boellstorff, 1978). The SIDP's rolling topography has developed continuously since the Yarmouth interglacial of 300,000 years ago (Prior, 1991). Consequently, the SIDP has experienced extensive erosion. Pennsylvanian shale is now exposed on many hillsides. Some of the shale remains in place; some has broken loose and occurs interbedded with loess- and till-derived colluvium.

Shale was defined by Pettijohn (1949) as a laminated or fissile claystone or siltstone that had been buried by geologic processes at some point. When that shale is found near the earth's modern surface, the soils form in it often inherit many shale properties such as texture and pH. Soils may have a range of particle size distributions determined by the original composition of shale. Shale has a wide range of texture; its clay content has been reported to range from 17% to more than 50% by weight (Boggs, 1992; Prothero and Schwab, 2004). Slusher (1960) studied some soils formed in shale in southern Iowa that had clay contents ranging from 23 to 79% in the lower horizons. Peterson (1946) reported that many shales in Iowa are acidic. He attributed this acidity to the oxidation of sulfur in pyrite, forming sulfuric acid when it exposes to air and water. Slusher (1960) also found soil reaction was acidic – below 6. He also identified kaolinite, illite, muscovite and quartz in the lower horizons of two pedons of his study.

The pedogenic relevance of this geologic history is that a complex range of parent materials may be found on an individual hillslope of the SIDP, yet the predictability of where a given parent material will be found can be challenging. Given that matrix mineralogy, architecture and color are generally inherited in even well-developed sola, the identification

of each parent material is essential in deducing pedon formation and classification (Schaetzl and Anderson, 2005; Oganessyan and Susekova, 1995). Actually, the importance of identifying parent materials was recognized by Hilgard (1860). He suggested that this is one of the single most important activities for pedologists.

Ideally, different parent materials within a solum can be distinguished by lithologic discontinuities that are identifiable in the field and confirmed in the laboratory (Schaetzl, 1998). Wang and Arnold (1973) suggested that lithological discontinuities are observed first in the field by detecting abrupt change in texture, structure, consistency or horizon boundaries. The absence of lithologic discontinuities often – but not always - means the soil was formed in a uniform parent material (Chadwick et al., 1990; Beshay and Sallam, 1995). An immediate confounding factor is that discontinuities can be pedogenic or geologic. Where they are not coincident, pedogenic discontinuities usually exhibit gradual changes while geologic discontinuities are abrupt (Schaetzl and Anderson 2005, Smeck et al. 1968).

There are many different approaches for detecting lithologic discontinuities. Each entails examining depth trends of some soil feature such as total sand content, content of a sand fraction, total silt content, ratio of sand /silt, or mineralogical differences (Schaetzl, 1998). A break in any of these features suggests the presence of a lithologic discontinuity (Schaetzl and Anderson, 2005). However, pedologists recognize that it is not easy to detect lithologic discontinuities when younger parent materials gradually accrete onto older parent materials and/or if different parent materials share primary mineral provenance (Ruhe and Olson, 1980). Soil welding may mask the discontinuity between layered parent materials (Ruhe and Olson, 1980). McDonald and Busacca (1990) suggested that when the rate of

addition of loess is less than the rate of pedogenesis, the profile gets thicker, especially in the B horizon; yet, no lithologic discontinuity seems to occur. Another example of a “disappearing” discontinuity is when sand-size fragments – especially in shale – weather and/or disintegrate to smaller particles (Smeck and Wilding 1980). Those authors also noted sand weathering can lead to differences in the ratios of resistant minerals such as Ti and Zr, which in turn can result in identification of extra or too few parent materials.

Soil plasma includes all components of soil materials that are capable of moving initially, i.e., eroded materials are not considered soil plasma (Schaetzl and Anderson, 2005). This mobility of soil plasma during pedogenesis is yet another challenge in detecting lithologic discontinuities. That is why Smeck and Wilding (1980) recommended discontinuities should be detected using immobile components that are resistant to weathering. This is also why Tsai and Chen (2000) used the sand: silt ratio to detect lithologic discontinuities. And it is why the use of pH, CEC, EC, organic matter content, base saturation, clay content, clay mineralogy and/or soil color is generally avoided because they can result in erroneous parent material identification (Schaetzl and Anderson 2005).

In 2009, as part of the Iowa Cooperative Soil Survey personnel from NRCS re-examined Gosport (Fine, Illitic, Mesic, Oxyaquic Dystrudept) map units and collected characterization pedons from MLRA 108 and 109 in order to investigate whether or not a new series needed to be created. The Gosport series was established in 1938 as a moderately deep series because the surveyors at that time did not closely exam the shale. It is thought they assumed the presence of any shale implied a Cr horizon. The MLRA team decided to remap Gosport map units after they sampled and investigated many Gosport soils for ponds

and animal waste lagoons as well as examining Gosport locations being used in the Conservation Reserve Program (CRP). During these investigations they discovered that plant roots actually went past the original Cr horizon that was described in older soil surveys.

The goal of this paper is to classify pedons sampled as Munterville by the NRCS MLRA 108 field team and to evaluate various lines of evidence for lithological discontinuities in these pedons.

Materials and methods

Study area and field work

As part of the remapping project of the soil map units in MLRA 108 (Illinois and Iowa Deep Loess and Drift) and 109 (Iowa and Missouri heavy till plain) in 2009 by the MLRA soil scientists, a number of pedons were collected for laboratory analysis. The ones of interest to this study are those representing Gosport soil map units. In order to maximize similarity in Pleistocene landscape evolution between locations, we used only pedons from the Des Moines River Valley. This resulted in eight pedons, with one from each of the following counties: Mahaska, Monroe, Davis, Jefferson, Van Buren, Keokuk, Lucas and Marion (Figure 4.1). Each pedon was identified using the releve method of statistics which is known in pedology as “representative pedons.” Readers interested in releve statistics are encouraged to examine (Minnesota Department of Natural Resources Staff, 2007). Each pedon was collected as one 7-cm diameter soil core extending 1.5 m deep. All cores were taken using a truck mounted soil sampler (Giddings’ Machine Company, Windsor, CO). All pedons locations were recorded using a handheld Garmin-GPS Map 76 unit. Other pertinent

field conditions such as slope were determined via standard NRCS field methodologies. We used the Iowa Soil Properties and Interpretations Database (ISPAID) to determine the occurrence and distribution of Gosport and Munterville soil map units. The digital maps were obtained from the Natural Resources Geographic Information Systems Library (2011). We also used ArcGIS 9.3 software.

Pedon description

Pedons were described according to the methods in Schoeneberger and others (2002). Horizon type, horizon depth, boundaries between horizons, texture by feel, structure, consistence, presence of redoximorphic features, clay films, roots and pores were determined for each pedon. Soil color was determined by comparing soil samples to a Munsell Soil Color Chart.

Physical and chemical laboratory analyses

Soil samples representing all of the horizons of each pedon were air dried, ground and then sieved through a 2 mm sieve in order to separate the fine earth materials from the coarser materials, although due to soft rock and other parent materials involved no coarse material was identified.

Soil texture was determined by the pipette method (Pansu and Gautheyrou, 2006). Soil organic carbon was determined according to the dry combustion method described by Soil Survey Staff (2004) with a LECO LC2000 (LECO, 2009). Approximately 0.25 g of each soil horizon was used to determine both carbon and nitrogen percentage. Total C (TC) was assumed to be equal to total organic C in horizons where the pH was ≤ 6.8 because acid

conditions decrease the probability of inorganic carbon sources. Soil pH of each soil horizon was measured in water and CaCl_2 with an Orion pH (Thermo Scientific, Beverly, MA, USA) meter according to Sparks (1996). We used a 1:1 volume soil to water solution and a 1:2 volume of soil to 0.01 *M* CaCl_2 solution.

Cation exchange capacity (CEC) was measured by Na-saturation displacement using the centrifuge method (Soil Survey Staff, 2004). Base saturation was determined by extracting Ca^{2+} , Mg^{2+} , Na^+ and K^+ by displacement with 1*N* NH_4OAc at pH 7.0. The extracted cations were determined by atomic absorption spectrometer (PerkinElmer Instruments, 2009).

Clay mineralogy for selected horizons was determined according to Poppe and others (2001). In brief, approximately 45 g of the selected soil samples were weighed in a one liter beaker. CaCO_3 was removed by using 1% acetic acid. Organic matter was removed by adding 3% H_2O_2 gradually until foaming ceased. Sodium hexametaphosphate was used as a dispersion reagent. The clay fraction was isolated after dispersion and settling according to Stokes' Law. Each clay suspension was coagulated by adding MgCl_2 and excess MgCl_2 was removed by washing the sample with distilled water and then 95% ethanol. The isolated clay was frozen at -80 °C and then dried using a freeze-dryer. Oriented mounts on glass slides were prepared. Each sample was suspended in distilled water and filtered through a 47 mm in diameter Millipore cellulose filter paper using Millipore filtration apparatus. The filter paper with the remaining clay on it was wrapped on a 200 ml glass beaker with the clay film up and then transferred to a labeled glass slide. Each Mg-saturated clay sample was treated with 1:1 glycerol: water solution before x-ray analysis. A separate sample was treated with 1*M* KCl

and similarly prepared on a glass slide. We used CuK α radiation from Siemens D 5000 X diffractometer operated in θ -2 θ mode and equipped with a solid state Li(Si) detector and θ -compensating slits on both sides of the sample. The scanning speed was 0.05° 2 θ /minute.

Clay mineral peaks in the XRD patterns were identified and then quantified. We quantified intensities of clay minerals using the following equation: area = height of the peak x half height width (Moore and Reynolds, 1997). After determining areas of all peaks, we summed all of their areas together in order to calculate the percentage of each clay mineral using the following equation: clay mineral% = (its peak area / total area) x 100. It is important to recognize this method has significant limitations such as when multiple peaks are close together and when the background component is difficult to identify at low angles (Moore and Reynolds, 1997).

Classification

All of the surface and subsurface horizons were classified following the criteria of the US Soil Taxonomy (Soil Survey Staff, 2010). A mollic epipedon must have the following: (1) 0.6% or more organic carbon (2) its dominant moist color has value and chroma of three or less (3) a minimum thickness of 25 cm and (4) a base saturation of 50 or more determined by NH₄OAc. If a epipedon identification is not mollic then it can be umbric, melanic, anthropic, plaggen or ochric although pretty much only mollic and ochric epipedons are ever identified in the study region. For a subsurface diagnostic horizon to be an argillic horizon, it generally must have argillans and at least 1.2-times the clay content of A or E horizon, whichever has less clay. When the upper sola has more than 40% clay, the argillic horizon must have both argillans and at least 8% (absolute) more clay than the overlying horizon with

the least clay content. When the upper sola has less than 15% clay, the argillic horizon must exhibit argillans or clay bridging and at least a 3% (absolute) increase in clay content. When the Bt horizon formed in a parent material that differs from the one in which the overlying horizon formed, we considered only the existence of clay films. To completely classify the study pedons we followed the Keys to Soil Taxonomy (Soil Survey Staff, 2010).

Detecting lithologic discontinuities

Three laboratory methods were used to detect lithologic discontinuities. They are total sand as a depth function (Oertel and Giles, 1966), sand: silt ratio as a function of depth (Tsai and Chen, 2000) and total silt as a depth function (Meixner and Singer, 1981). Evaluation of each method was via comparison to field descriptions as well as cross-method comparisons.

Results and Discussion

Gosport and Munterville soils are distributed in sixteen counties in Iowa (Figure 4.1). Their map units occupy 42620 hectare (0.29%) of Iowa's land area. Figure 4.2 shows the distribution of Gosport and Munterville SMU's across the eight counties of interest in the Des Moines River valley. Marion and Monroe Counties have 10.6 and 7.4 % of their area mapped as Gosport or, now, Munterville. The extent of Gosport and Munterville in other counties is much less. For example, Jefferson and Keokuk Counties have just 0.2 and 0.03%, respectively.

Gosport and Munterville soils form in multiple parent materials. The lower parent material is Pennsylvanian shale or interbedded shale and limestone. The upper parent material is Pre-Illinoian till, Peoria loess, or local colluvium. Given that both form from the

same parent materials and on the same landscape, it is not surprising they share many common properties such as color, texture (but not clay distribution), pH and organic carbon content.

Both soils are brown to yellowish brown in the upper 70 cm of the soil profile (Table 4.1 and official series descriptions). Below that the color is often gray and even black. The gray color is inherited from the Pennsylvanian shale. It is not an indicator of drainage class, which is moderately well drained. The black color is due to coal and/or carboniferous shale fragments in the lower horizons. In general, soil texture class is clayey – more specifically, often silty clay (Table 4.1). The pH of some horizons of some of the pedons is unusually acidic (Table 4.2), at least by the normal standards of the upper Mississippi River valley. Table 4.2 shows the total carbon distribution in the pedons studied. In most horizons the TC is equal to organic carbon content since no carbonate minerals are present; however, the presence of carbon-rich shales and coal causes elevated TC in the lower sola of pedons from Monroe and Keokuk Counties (Table 4.2).

Each pedon has an ochric epipedon with the thickest “mollic epipedon colors” being only 13 cm (Table 4.1). All eight pedons have argillic horizons. The evidence for argillic horizons are field descriptions that note argillans, i.e., Bt horizons and laboratory measured clay enrichment in the Bt horizons that meet the criteria given in Soil Taxonomy (Soil Survey Staff, 2010).

By definition, pedons that have ochric epipedons and argillic horizons are either Alfisols or Ultisols (Soil Survey Staff, 2010). The difference between Alfisols and Ultisols is whether base saturation is greater than 35% (by sum of cations) at a critical depth, which is

determined using solum and argillic horizon thickness as well as depth to a parent material change (Soil Survey Staff, 2010). Five pedons are clearly Alfisols. They are from Mahaska, Monroe, Jefferson, Keokuk and Lucas Counties (Tables 4.2 and 4.4). One pedon, Marion pedon, is clearly an Ultisol. The other two are ambiguous, depending on where the shale parent material is identified and on how one interprets the “35%” base saturation rule.

Since the soil moisture regime of all moderately well drained soils in MLRA 108 and 109 is udic, these eight pedons are Udalfs and Udufts. Given that they have no other diagnostic features, they are Hapludalfs and Hapludults, respectively (Soil Survey Staff, 2010). The presence of redoximorphic features at 40 cm and deeper results in their respective subgroup classification as being Oxyaquic Hapludalfs and Oxyaquic Hapludults.

To completely classify soil pedons under study down to the family level, we determined particle-size, mineralogy and CEC classes within their control section of each pedon (Table 4.3). We followed the criteria of determining control section in the Soil Taxonomy (Soil Survey Staff, 2010). In brief, we started the control section of each pedon from the top of the argillic horizon. If the argillic horizon thickness was more than 50 cm, we used only the upper 50 cm of this thickness. However, if the argillic horizon thickness is less than 50 cm, we used its entire thickness (Table 4.3).

Family particle-size class was determined by calculating the weighted average of clay content within each pedon’s control section. Our results show that the weighted average of clay content ranges from 40 to 60%, which qualifies the particle-size class to be fine (Tables 4.3 and 4.4). Within the control section, family mineralogy class was determined by identifying the clay minerals peaks of the XRD patterns and then quantifying them. To

identify the peaks, we considered the degrees 2 theta and the concomitant d-spacing and then we compared the d-spacing values with what is stated in the literature. In fact, there are a variety of layer silicate clay minerals within the control sections of study pedons. These layer silicate clay minerals, smectite, vermiculite, illite and kaolinite were quantified as mentioned in the methods section (Table 4.3) resulting in some soil pedons are mixed and others are kaolinitic.

To determine the family activity class, we calculated the ratio between CEC and clay content. Table 4.3 shows the ratio ranges from 0.4 to 0.6 in most of the pedons. This makes the pedons “active.” However, the Mahaska pedon has a 0.62 ratio, which qualifies the cation exchange activity class to be superactive (Table 4.3). Significantly, four pedons are kaolinitic and active at the same time (Davis, Jefferson, Van Buren and Keokuk). We attribute this to the high content of organic carbon in these pedons within the control section. Organic carbon content in these pedons ranges from 0.3 to 0.8 % (Table 4.2). The mean annual soil temperature is about 10 to 12°C; that qualifies the soil temperature class to be mesic.

In sum, the complete taxonomic classification of the Alfisols group of pedons is fine, mixed, smectitic or kaolinitic, active or superactive, mesic Oxyaquic Hapludalfs (Table 4.4). The Ultisol pedon(s) is classified as fine, mixed or kaolinitic, active, mesic Oxyaquic Hapludults. Our interpretation is both types of pedons occur in Munterville, map units with the Ultisol pedons representing a minor component that is not mappable as a separate series. This is further discussed later.

To evaluate where lithologic discontinuities occurred, we used total sand, sand: silt ratio and total silt as depth functions (Figures 4.3 to 4.6) and compared each trend breaks to the lithological discontinuities described in the field. The major landscape position of the Gosport series is the backslope position. Its occurrence in this landscape position results in the upper portion of the sola being formed in glacial till, loess or local colluvium. We compared the lithologic discontinuities found by using laboratory analyses with those found in the field in order to find whether they match as well as to identify the parent materials in each pedon. In order to field identify lithologic discontinuities we relied on transitions in soil texture and the "soapy" feel of the "shaly stuff." Depth distributions of total sand indicated lithological discontinuities at the same depths as those detected in field descriptions (Figure 4.5). Lithologic discontinuities detected by using depth trends of sand: silt ratio mostly matches and a few of them do not match with those detected in the field. For example, lithologic discontinuities detected in the laboratory analyses are more compared with what was detected in the field, as it appears in the pedons from Davis and Van Buren Counties, with what was detected in the field (Figure 4.6). Conversely, total silt results – data are not shown – do not match at all with field detections.

The x-ray diffraction patterns of all pedons under study are available in the appendix of this thesis; however, we chose only two examples of these pedons representing an example of an Alfisol and another example of an Ultisol. The x-ray diffraction patterns of Lucas and Marion pedons (Figures 4.3 and 4.4) show clay mineralogy variability between the upper horizons (Ap or Bt1 horizons) and the lower horizons (2Bt2 or 2Cr horizons). For example, in Lucas pedon (Figure 4.3), the Ap horizon has vermiculite, illite, kaolinite and

lepidocrocite that is slightly different from the mineralogy of both the 2Bt2 and 2C3 horizons which have zeolites in addition to what found in the upper horizons. Both of those horizons do not have any lepidocrocite. However, they have two strong peaks (d-spacing 7.96 and 3.97 Å). We identified these peaks as representing heulandite (a zeolite mineral). Zeolites have been detected as components of sedimentary rocks, especially of volcanic origin (Boettinger and Ming, 2002). Volcanic ash has been recognized in Iowa within the Pre-Illinoian Till glaciation (Boellstorff, 1978). Similarly, Figure 4.4 shows the same difference between the upper horizon and the lower horizons of Marion pedon. Overall, by comparing the depth at which the clay mineralogy changes with detected lithologic discontinuities in the field descriptions, we found both match.

Considering what Smeck and Burras did in (2006) and what Goebel and others did in (1989), we designed a suggested stratigraphic landscape showing the possible positions of Alfisols or Ultisols occurrence in study area (Figure 4.7). We suggest that Munterville may form in the positions one, two and five because the majority of the sola exist in non shaly materials or in an interbedded shale and limestone layer that causes the base saturation to be higher than 35%. However, Ultisols may form in the positions three and four because acidic shale participates significantly in the sola which causes the base saturation to be less than 35% (Figure 4.7).

Conclusions

Remapping of Gosport soil map units ended up identifying pedons that are Alfisols and pedons that are Ultisols. Both are part of the range of field properties now considered part of Munterville which is officially a fine, mixed, active, mesic, Oxyaquic Hapludalf.

Identification of lithologic discontinuities in these pedons remained problematic because different approaches resulted in differing interpretations.

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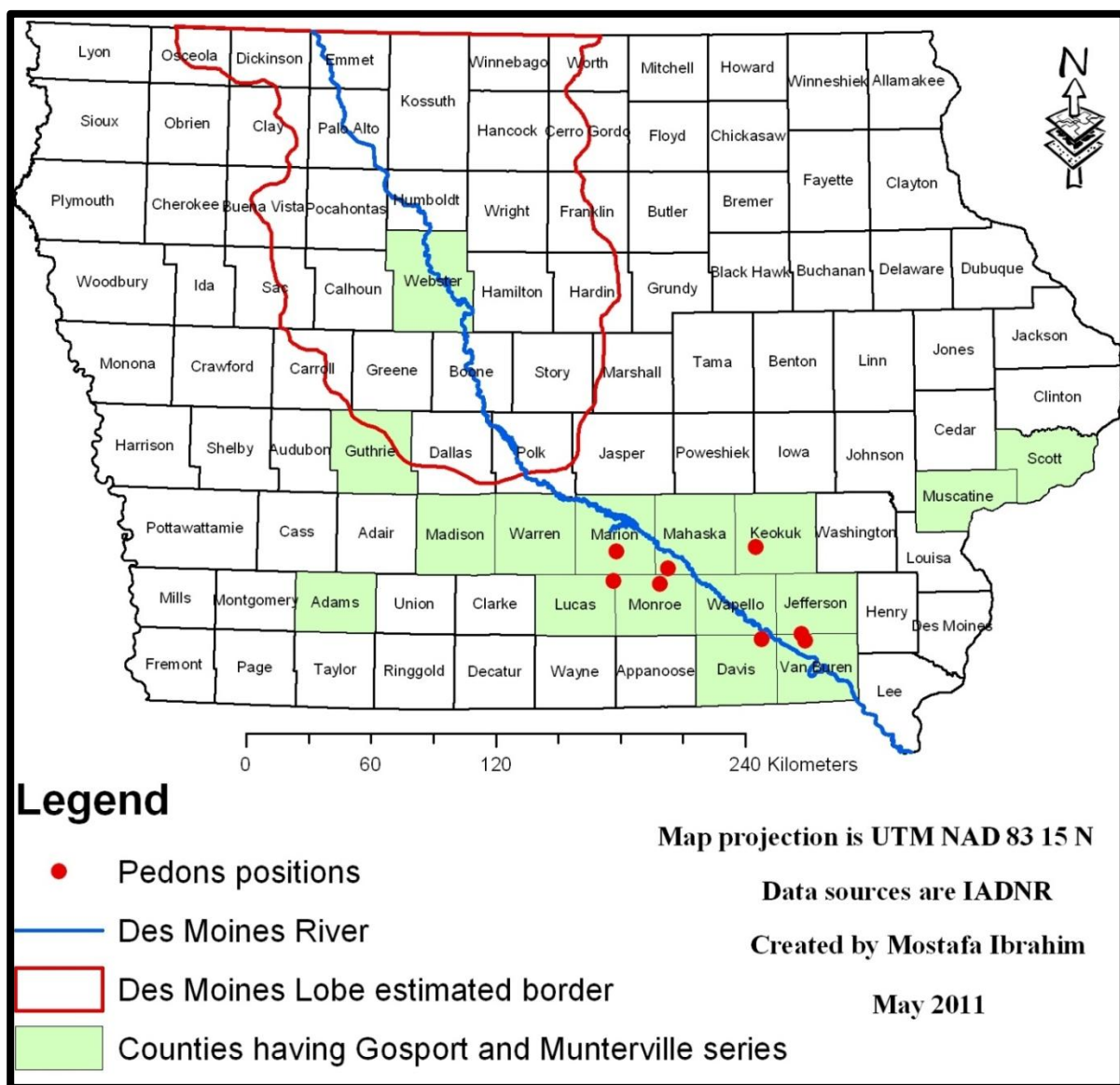


Figure 4.1. Distribution of Gosport and Munterville series across Iowa and locations of study pedons.

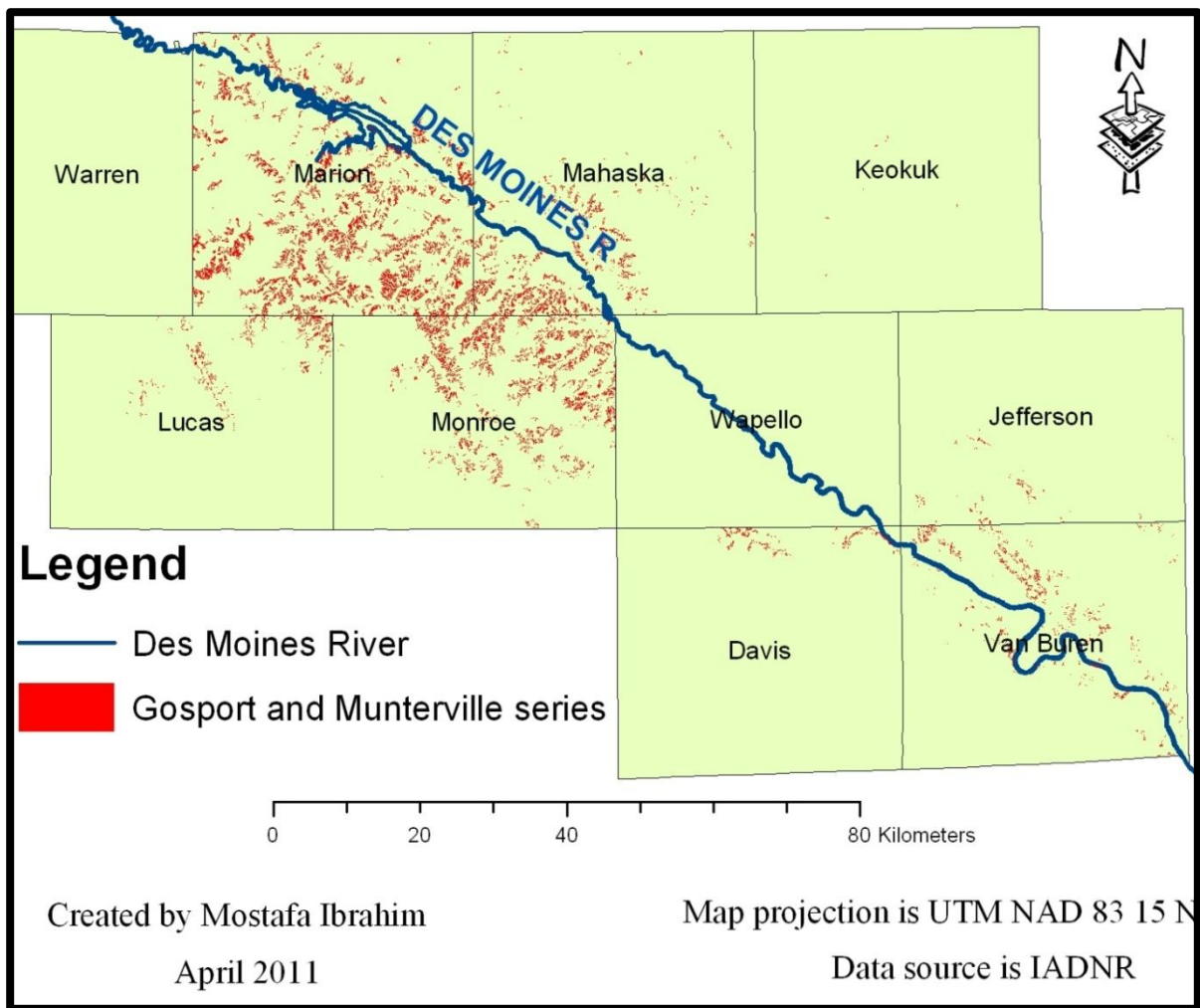


Figure 4.2. Distribution of Gosport and Munterville series in study counties in Iowa.

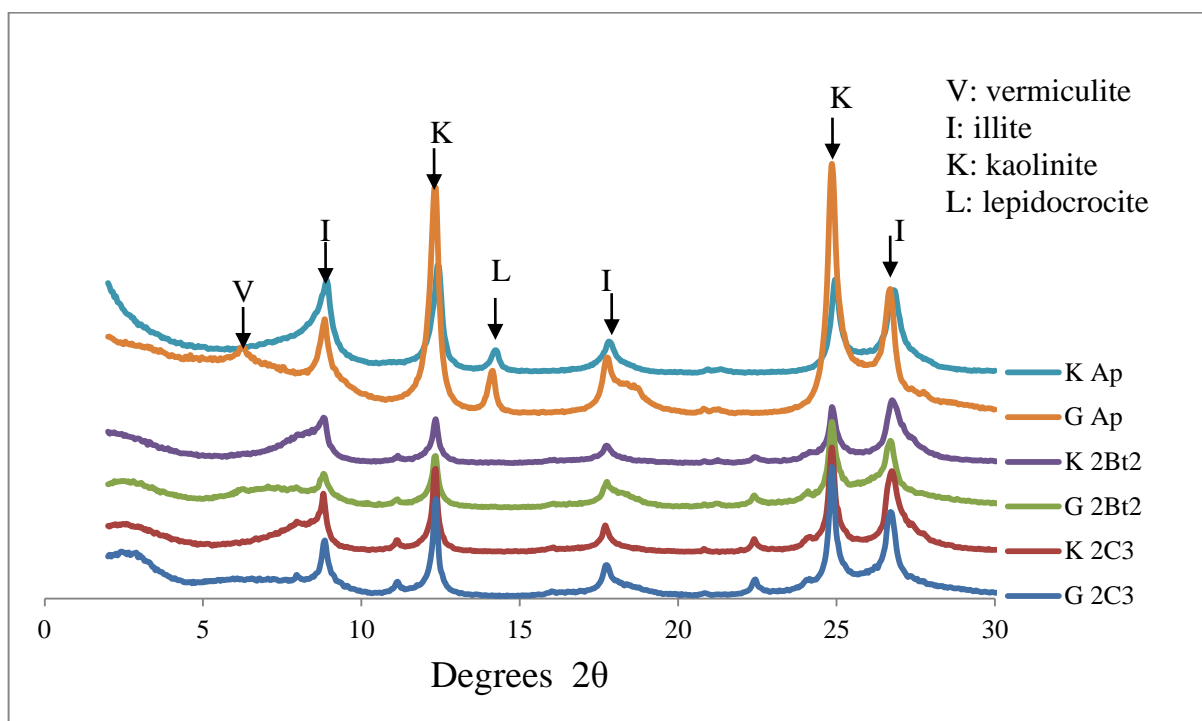


Figure 4.3. X-ray diffraction patterns of < 2 μm clay of the study pedon in Lucas County.

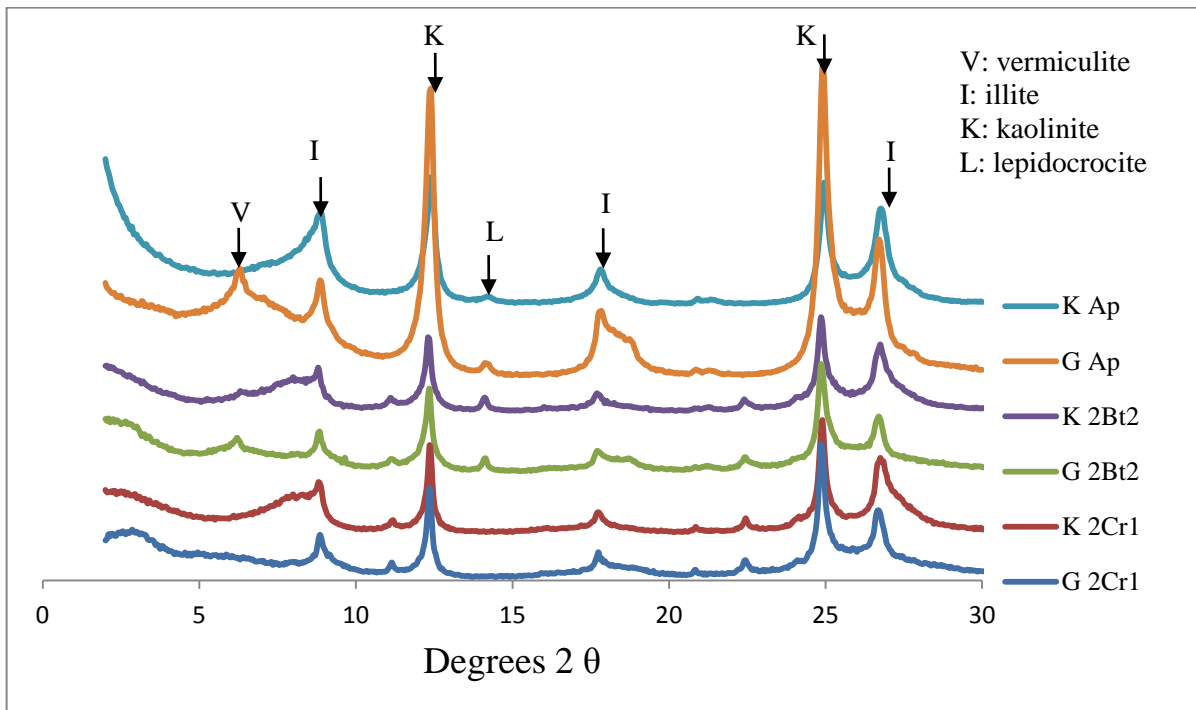


Figure 4.4. X-ray diffraction patterns of $< 2 \mu\text{m}$ clay of the study pedon in Marion County.

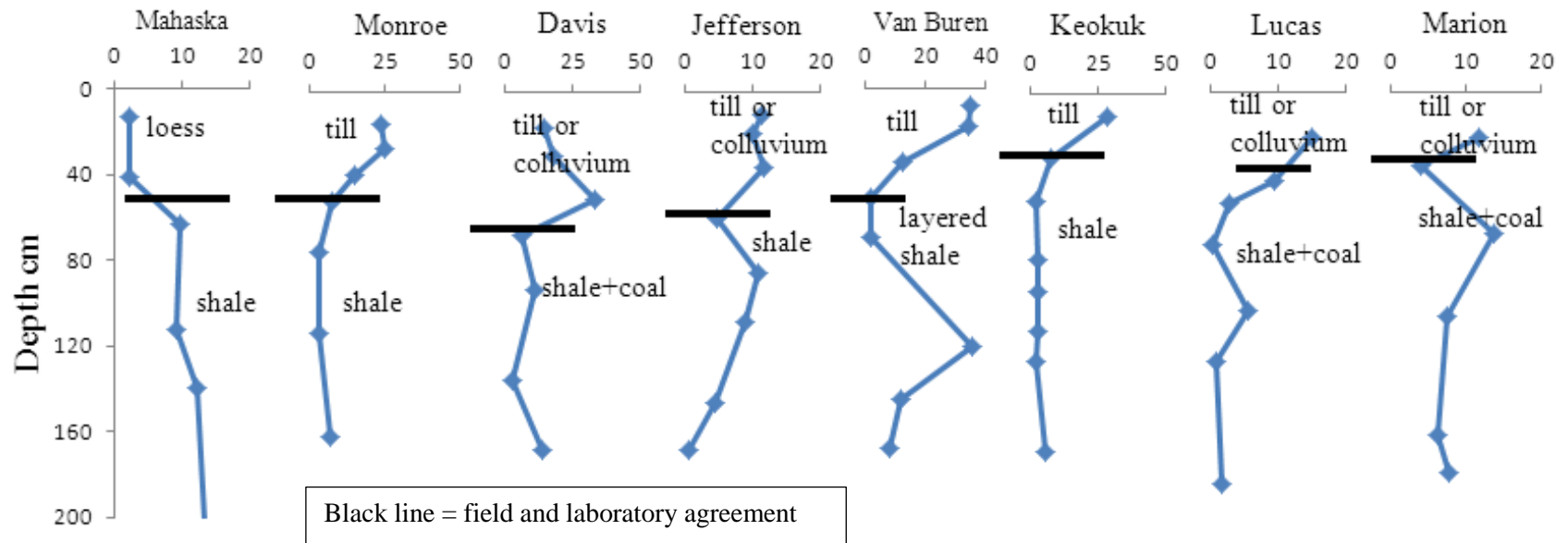


Figure 4.5. Lithologic discontinuities using total sand as a depth function.

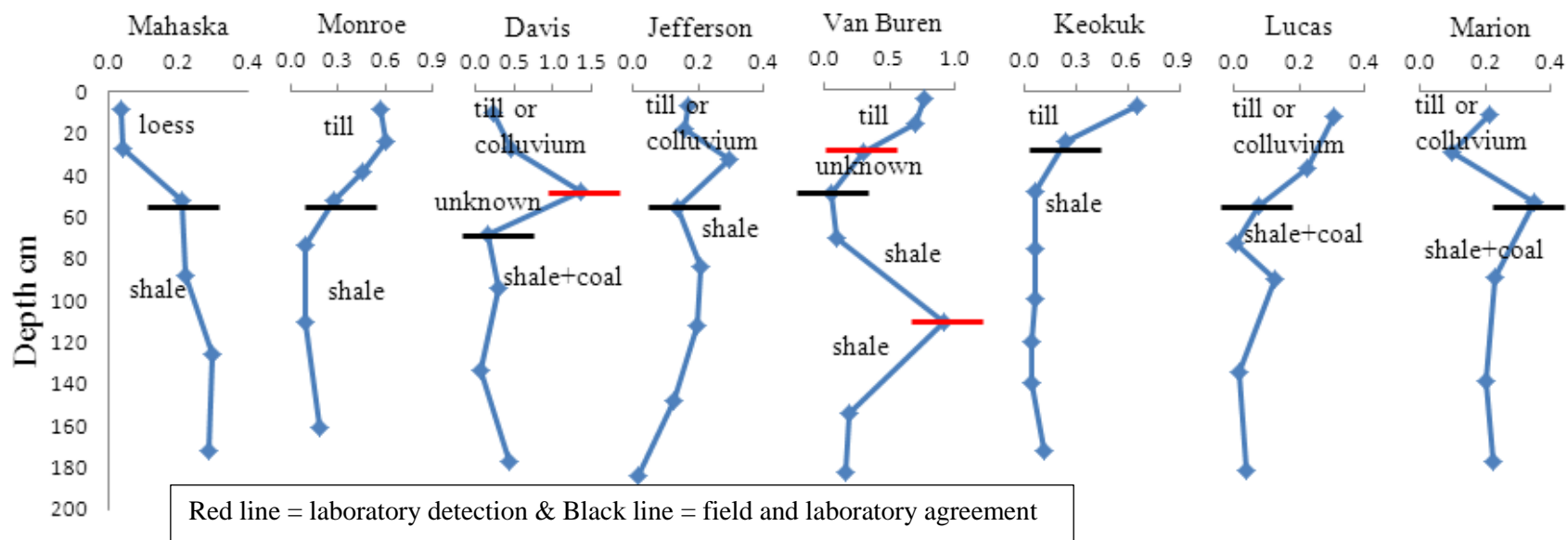


Figure 4.6. Lithologic discontinuities using sand: silt ratio as a depth function.

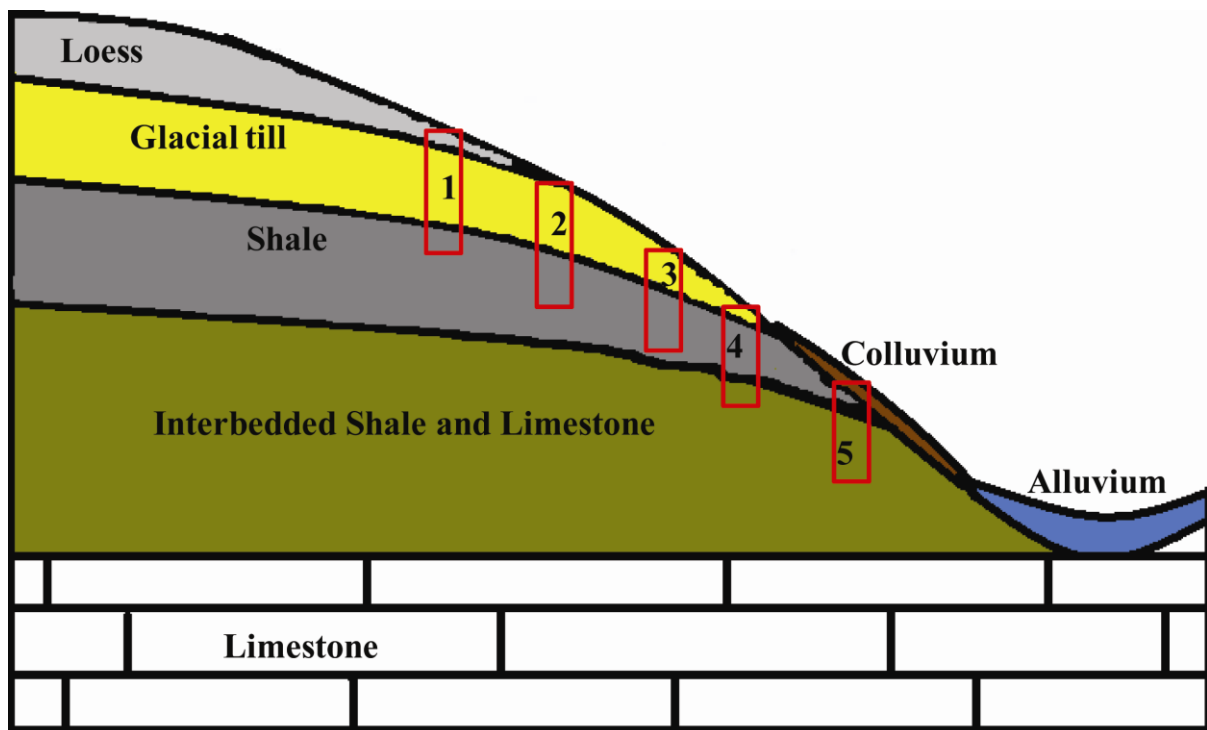


Figure 4.7. Possible positions of Munterville soils or Ultisols in study pedons.

Table 4.1. Physical and morphological properties of study pedons.

Pedon	Depth (cm)	Horizon	Sand (%)	Silt (%)	Clay (%)	Sand/silt	Texture†	Horizon boundary‡	Color (moist)	Structure §	Clay films
Mahaska	0-13	Ap	2.2	63.4	34.3	0.0	SiCL	C S	10YR4/3	1 f sbk	
	13-41	Bt1	2.0	48.4	49.6	0.0	SiC	C S	10YR5/3	2 m sbk	yes
	41-63	2Bt2	9.6	46.6	43.8	0.2	SiC	C S	10YR5/4	2 m sbk	yes
	63-112	2Bt3	9.1	42.0	48.9	0.2	SiC	G S	2.5Y5/2	2 m sbk	yes
	112-140	2C	12.2	41.6	46.1	0.3	SiC	G S	10YR5/4	M	
	140-203	2Cr	13.2	46.3	40.5	0.3	SiC	-	10YR5/4	M	
Monroe	0-18	Ap	24.0	42.6	33.4	0.6	CL	C S	10YR4/3	1 f sbk	
	18-33	Bt1	24.9	41.4	33.7	0.6	CL	C S	10YR4/4	2 m sbk	yes
	33-48	Bt2	15.4	34.2	50.4	0.5	C	C S	10YR5/4	2 m sbk	yes
	48-64	2Bt3	7.6	27.2	65.3	0.3	C	C S	10YR5/4	2 m sbk	yes
	64-94	2Bt4	3.6	40.3	56.1	0.1	SiC	G S	5Y5/2	2 m sbk	yes
	94-142	2C	3.6	41.2	55.1	0.1	SiC	G S	N5/0	M	
	142-203	2Cr	7.4	40.0	52.6	0.2	SiC	-	2.5Y4/1	M	
Davis	0-20	Ap	14.7	64.3	21.0	0.2	SiL	C S	10YR4/3	1 f sbk	
	20-36	Bt1	18.5	39.0	42.5	0.5	C	C S	10YR5/4	2 f sbk	yes
	36-61	2Bt2	33.1	24.3	42.6	1.4	C	C S	10YR5/4	2 m sbk	yes
	61-81	2BC	6.3	36.3	57.5	0.2	C	G S	10YR5/2	2 m sbk	
	81-112	2C	11.1	37.6	51.3	0.3	C	G S	10YR5/2	M	
	112-163	2Cr1	3.0	37.3	59.7	0.1	C	G S	10YR6/2	M	
	163-203	2Cr2	13.8	30.7	55.4	0.4	C	-	N2.5/0	M	
Jefferson	0-13	A	11.5	66.9	21.6	0.2	SiL	A S	10YR3/2	2 f gr	
	13-23	E	10.1	63.3	26.6	0.2	SiL	A S	10YR4/2	1 m pl	
	23-43	Bt1	11.7	39.8	48.6	0.3	C	C S	10YR4/3	2 m sbk	yes
	43-71	2Bt2	4.9	35.7	59.4	0.1	C	C S	10YR5/4	2 m sbk	yes
	71-102	2BC	10.8	52.5	36.7	0.2	SiCL	C S	2.5Y6/1	2 m pr	
	102-130	2C1	9.1	46.5	44.4	0.2	SiC	C S	10B7/1	M	
	130-176	2C2	4.5	36.5	59.0	0.1	C	G S	5Y5/1	M	
	176-203	2C3	0.6	31.7	67.7	0.0	C	-	2.5Y6/1	M	
Van Buren	0-10	A	35.1	45.8	19.2	0.8	L	A S	10YR4/2	1 f gr	
	10-21	E	34.2	48.7	17.1	0.7	L	A S	10YR5/2	1 tk pl	
	21-41	Bt1	12.5	41.4	46.1	0.3	SiC	C S	7.5YR5/4	2 f sbk	yes
	41-61	2Bt2	2.0	33.4	64.5	0.1	C	G S	2.5Y7/2	2 m sbk	yes
	61-84	2BC	2.4	23.7	73.9	0.1	C	G S	5Y6/2	1 m sbk	
	84-145	2C1	35.4	38.5	26.1	0.9	L	G S	2.5Y7/2	M	
	145-175	2C2	12.1	62.7	25.3	0.2	L	G S	5Y7/2	M	
	175-203	2Cr	8.2	50.2	41.6	0.2	SiC	-	N6/0	M	

Table 4.1. (continued)

Pedon	Depth (cm)	Horizon	Sand (%)	Silt (%)	Clay (%)	Sand/ silt	Texture †	Horizon boundary‡	Color (moist)	Structure §	clay films
Keokuk	0-13	Ap	28.6	43.8	27.6	0.7	L	A S	10YR4/3	2 f gr	
	13-36	2Bt1	7.9	32.9	59.2	0.2	C	C S	10YR5/4	2 m sbk	yes
	36-61	2Bt2	2.5	37.6	60.0	0.1	C	C S	10YR5/4	2 m sbk	yes
	61-94	2BC	2.8	44.9	52.3	0.1	SiC	G S	2.5Y4/1	2 m sbk	
	94-112	2C1	2.9	46.8	50.2	0.1	SiC	G S	2.5Y3/1	M	
	112-135	2C2	2.8	68.6	28.5	0.0	SiCL	-	10YR5/4	M	
Lucas	0-20	Ap	15.0	49.4	35.5	0.3	SiCL	A S	10YR4/3	1 f sbk	
	20-40	2Bt1	9.6	42.6	47.8	0.2	SiC	C S	2.5Y6/3	2 m sbk	yes
	40-50	2Bt2	2.8	37.6	59.6	0.1	C	C S	2.5Y5/2	2 m sbk	yes
	50-69	2BC	0.4	45.0	54.6	0.0	SiC	G S	N5/0	M	
	69-99	2C1	5.6	44.8	49.6	0.1	SiC	G S	N5/0	M	
	99-122	2C2	0.9	49.6	49.5	0.0	SiC	G S	N6/0	M	
	122-178	2C3	1.9	44.9	53.2	0.0	SiC	-	N6/0	M	
Marion	0-20	Ap	11.7	54.7	33.6	0.2	SiCL	A S	10YR4/3	1 f sbk	
	20-33	2Bt1	4.2	42.4	53.5	0.1	SiC	C S	10YR6/3	2 f sbk	yes
	33-64	2Bt2	13.9	39.9	46.2	0.3	C	G S	2.5Y5/2	2 m sbk	yes
	64-102	2BC	7.6	32.8	59.6	0.2	C	G S	N6/0	1f sbk	
	102-156	2C	6.2	30.6	63.2	0.2	C	A S	N5/0	M	
	156-173	2Cr	7.9	35.2	56.9	0.2	C	-	N2.5/0	M	

† Texture: SiCL (silty clay loam), SiC (silty clay), CL (clay loam), C (clay), SiL (silt loam),

L (loam).

‡ Horizon boundary: C (clear), S (smooth), G (gradual), A (abrupt).

§ Structure: 1 (weak), 2 (moderate), f (fine), m (medium), tk (thick), sbk (subangular blocky),

M (massive), gr (granular), pl (platy).

Table 4.2. Chemical properties of study pedons.

Pedon	Depth (cm)	Horizon	OC %	pH(1:1) H ₂ O	pH(1:2) CaCl ₂	Exchangeable cations(cmol _c kg ⁻¹)				CEC (cmol _c kg ⁻¹)	BS %
						Ca ⁺⁺	Mg ⁺⁺	K ⁺	Na ⁺		
Mahaska	0-13	Ap	2.7	5.26	4.83	10.9	6.97	0.70	0.13	25.3	73.9
	13-41	Bt1	0.6	4.46	4.13	11.3	10.03	0.65	0.29	32.9	67.6
	41-63	2Bt2	0.4	4.96	4.35	8.6	8.67	0.45	0.36	24.8	72.9
	63-112	2Bt3	0.3	6.26	5.55	8.8	8.50	0.20	0.48	21.5	83.6
Monroe	0-18	Ap	2.6	6.54	6.45	15.3	2.55	0.30	0.11	20.3	89.9
	18-33	Bt1	1.2	6.48	6.19	12.2	2.21	0.25	0.10	19.9	74.0
	33-48	Bt2	0.9	6.61	6.16	16.9	3.06	0.35	0.13	26.6	76.9
	48-64	2Bt3	0.8	6.17	5.79	27.1	3.40	0.40	0.15	40.8	76.1
Davis	0-20	Ap	1.3	5.87	6.14	7.9	2.89	0.20	0.12	15.6	71.2
	20-36	Bt1	0.5	4.23	3.88	3.2	3.06	0.30	0.11	20.0	33.4
	36-61	2Bt2	0.4	4.17	3.70	1.8	3.23	0.35	0.15	20.0	27.8
	61-81	2BC	0.5	4.10	3.60	1.6	3.06	0.25	0.14	20.6	24.5
	81-112	2C	0.5	4.12	3.55	2.3	3.23	0.20	0.15	16.0	36.8
Jefferson	0-13	A	2.1	5.7	5.21	7.4	2.89	0.20	0.16	16.8	63.5
	13-23	E	0.7	5.35	4.46	4.5	2.38	0.20	0.18	14.7	49.3
	23-43	Bt1	0.6	4.93	4.04	5.6	4.76	0.35	0.28	26.2	42.0
	43-71	2Bt2	0.3	4.66	3.98	5.8	5.44	0.35	0.27	31.8	37.3
	71-102	2BC	0.2	4.67	4.23	4.6	4.40	0.20	0.29	16.7	56.8
Van Buren	0-10	A	1.4	5.29	4.99	3.7	1.53	0.20	0.09	11.0	50.1
	10-21	E	1.0	5.15	4.65	2.6	1.19	0.15	0.10	9.2	43.7
	21-41	Bt1	0.4	4.6	3.96	3.2	2.55	0.30	0.29	21.7	29.2
	41-61	2Bt2	0.4	4.41	3.67	1.5	2.04	0.40	0.15	29.1	14.1
	61-84	2BC	0.4	4.23	3.79	2.8	2.72	0.40	0.24	29.0	21.3
	84-145	2C1	0.2	4.57	3.85	1.1	1.36	0.15	0.12	6.2	44.4

Table 4.2. (continued)

Pedon	Depth (cm)	Horizon	OC %	pH(1:1) H ₂ O	pH(1:2) CaCl ₂	Exchangeable cations(cmol _c kg ⁻¹)				CEC (cmol _c kg ⁻¹)	BS %
						Ca ⁺⁺	Mg ⁺⁺	K ⁺	Na ⁺		
Keokuk	0-13	Ap	2.6	5.37	5.20	8.9	2.38	0.20	0.14	18.0	64.7
	13-36	2Bt1	0.6	4.74	4.13	5.6	2.38	0.35	0.17	27.2	31.2
	36-61	2Bt2	0.8	4.75	4.07	6.2	3.74	0.30	0.18	25.9	40.2
	61-94	2BC	1.2	5.17	4.67	12.9	4.42	0.35	0.18	26.7	66.9
	94-112	2C1	1.1	5.45	5.41	5.4	4.76	0.20	0.34	23.9	44.8
Lucas	0-20	Ap	2.6	5.35	5.14	11.6	3.40	0.25	0.11	24.9	61.7
	20-40	2Bt1	0.4	5.53	5.06	13.6	4.93	0.25	0.22	25.1	75.7
	40-50	2Bt2	0.3	5.58	5.27	10.6	5.27	0.25	0.31	23.2	70.8
	50-69	2BC	0.3	6.01	5.88	8.2	5.95	0.20	0.38	19.5	75.4
Marion	0-20	Ap	1.7	5.97	5.46	9.3	3.40	0.15	0.26	21.9	59.7
	20-33	2Bt1	0.5	5.05	4.36	5.0	3.06	0.15	0.14	23.5	35.5
	33-64	2Bt2	0.5	4.94	4.18	3.0	2.40	0.15	0.15	20.6	27.6
	64-102	2BC	0.3	4.55	3.80	1.7	1.50	0.25	0.14	22.7	15.9
	102-156	2C	0.3	4.13	3.56	2.0	1.40	0.30	0.15	20.8	18.4

Table 4.3. Parameters of the family level in classifying study pedons within their control section.

Pedon	Control section (cm)	Clay %	CEC ($\text{cmol}_c \text{ kg}^{-1}$)	CEC/clay	Smectite %	Vermiculite %	Illite %	Kaolinite %
Mahaska	50	47	29	0.62	50	20	5	25
Monroe	50	51	29	0.57	—	45	20	35
Davis	41	43	20	0.47	30	—	10	60
Jefferson	48	55	29	0.53	—	5	15	80
Van Buren	40	55	25	0.45	—	30	20	50
Keokuk	48	59	27	0.46	5	15	20	60
Lucas	50	55	24	0.44	—	30	40	30
Marion	44	48	21	0.44	—	30	30	40

Both clay content and CEC values were determined as a weighted average within their control sections. Briefly, if the control section contained one horizon, the value of clay content or CEC stayed the same. However, if the control section contained two horizons, each horizon value was multiplied by the thickness of this horizon; the two new values were summed and then divided by the total thickness of the control section.

Table 4.4. Classification of pedons under study.

Pedon	Classification (using the BS% value at the paralithic contact)	Classification (using the depth weighted average of BS% from the top of the argillic to the paralithic contact)
Mahaska	Fine, smectitic, superactive, mesic, Oxyaquic Hapludalfs	Fine, smectitic, superactive, mesic, Oxyaquic Hapludalfs
Monroe	Fine, mixed, active, mesic, Oxyaquic Hapludalfs	Fine, mixed, active, mesic, Oxyaquic Hapludalfs
Davis	Fine, kaolinitic, active, mesic, Oxyaquic Hapludalfs	Fine, kaolinitic, active, mesic, Oxyaquic Hapludults
Jefferson	Fine, kaolinitic, active, mesic, Oxyaquic Hapludalfs	Fine, kaolinitic, active, mesic, Oxyaquic Hapludalfs
Van Buren	Fine, kaolinitic, active, mesic, Oxyaquic Hapludalfs	Fine, kaolinitic, active, mesic, Oxyaquic Hapludults
Keokuk	Fine, kaolinitic, active, mesic, Oxyaquic Hapludalfs	Fine, kaolinitic, active, mesic, Oxyaquic Hapludalfs
Lucas	Fine, mixed, active, mesic, Oxyaquic Hapludalfs	Fine, mixed, active, mesic, Oxyaquic Hapludalfs
Marion	Fine, mixed, active, mesic, Oxyaquic Hapludults	Fine, mixed, active, mesic, Oxyaquic Hapludults

Chapter 5: General Conclusions

The argillic horizon occurs almost everywhere all over the world. Pedologists think that its formation needs high rainfall and trees vegetation; however, it occurs in arid regions with neither high rainfall nor forest ecosystem. Drainage systems affect significantly the argillic horizon formation. For example, open drainage systems favor its formation. In contrast, closed drainage systems inhibit its formation. Closed drainage systems, e.g., prairie potholes have special kinds of organisms such as cattails, sedges, reeds, diatoms and sponge specules that are avid consumers of silicon. This consumption of silicon inhibits new clay particles to form because silicon is depleted from the system. Also, CaCO_3 and Ca-silicate minerals co-inhibit the formation of argillic horizons. CaCO_3 can adsorb Si ions on its surface, also, Ca ions act as a bonding agent between clay particles resulting in the formation of larger particles and then inhibiting them from downward translocation. Moreover, the formation of Ca-silicate minerals consumes Si from the system and then inhibiting the neoformation of clay particles. In very rare cases, closed depressions might have argillic horizons (e.g., Rolfe series). However, these closed depressions are surrounded by soils formed in sandy parent materials such as outwash or alluvium that makes these depressions to act as if they are open drainage systems.

What forms some special horizons in soils such as argillic, albic, spodic and even lamellae is clay-sized particles movement. All pedologists believe in the downward movement of clay particles and no one has investigated before the upward movement of these particles. In chapter 3 of my dissertation, we investigated this movement in the laboratory in sponges and sand columns and we found that clay particles can move all

directions, downward and upward. This upward movement inspired us to reinterpret the formation of some well-known pedological features such as lamellae, albic (E) and argillic horizons. For example, we hypothesized that upward movement of ground water and its fluctuation are the responsible for lamellae formation whereas clay particles are drawn up by water movement upwards. Also, in the albic (E) horizon water migrates in both directions upward and downward simultaneously after a rainfall event stops. This water movement in both directions draws clay particles with it and causes the decrease in clay particles in this horizon.

Migration of clay particles results in increasing the clay content in one horizon and a decreasing in another. Also, it forms clay films that strengthen the identification of the argillic horizon. We investigated the impact of clay movement in forming the argillic horizon in layered parent materials such as soil formed in SIDP geomorphic surface. Remapping previously mapped soils might result in new soils that are different from the original mapped ones. For example, we investigated some Gosport soil map units (fine, illitic, mesic, Oxyaquic Dystrudept) that was mapped in 1938 and we found them changed to either (fine , mixed or kaolinitic, active or superactive, mesic, Oxyaquic Hapludalf) or (fine, mixed or kaolinitic, active, mesic, Oxyaquic Hapludult).

In sum, the three chapters in my dissertation share a main goal of explaining how the clay particles move in the soil and the impact of this movement on soil horizonation. They may seem to be completely independent but in fact they are each of a part of the puzzle that pedologists face about where and why the matrix and plasma of soil behave the way they do.

Appendix 1

Pedon descriptions

Pedon ID	Mahaska
Classification	Fine, mixed, superactive, mesic, Oxyaquic Hapludalfs
Soil Map Unit	313D
Location	NE1/4, Sec. 27, T74N, R17W
Land use	Conservation Reserve Program (CRP)
Hillslope position	backslope
slope	16%
Parent material	Loess over shale
Ap--	0-13 cm; brown (10YR4/3) silty clay loam, weak fine subangular blocky structure; friable; many fine roots; few dark grayish distinct brown (10YR4/2) organic stains on all faces of peds; strongly acid; clear smooth boundary.
Bt1--	13-41 cm; brown (10YR5/3) silty clay, moderate medium subangular blocky structure; friable; many fine roots; common distinct brown (10YR4/3) clay films on all faces of peds; very strongly acid; clear smooth boundary.
2Bt2--	41-63 cm; yellowish brown (10YR5/4) silty clay, moderate medium subangular blocky structure; firm; many fine roots; common distinct brown (10YR4/3) clay films on all faces of peds; common fine distinct yellowish brown (10YR5/6) redoximorphic masses; very strongly acid; clear smooth boundary.
2Bt3--	63-112 cm; weak red (2.5YR5/2) silty clay, moderate medium subangular blocky structure; firm; common fine roots; common distinct dark gray (2.5YR4/1) clay films on all faces of peds; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; slightly acid; gradual smooth boundary.

2C-- 112-140 cm; yellowish brown (10YR5/4) silty clay, massive; firm; many medium prominent strong brown (7.5YR5/6) redoximorphic masses; gradual smooth boundary.

2Cr-- 140-203 cm; yellowish brown (10YR5/4) silty clay; massive; firm; many medium prominent strong brown (7.5YR5/6) redoximorphic masses.

Pedon ID Monroe

Classification Fine, mixed, active, mesic, Oxyaquic Hapludalfs

Soil Map Unit 313E2

Location SW1/4, Sec. 17, T73N, R17W

Land use Hay field/Alfalfa

Hillslope position backslope

slope 17%

Parent material Till over shale

Ap-- 0-11 cm; brown (10YR4/3) clay loam, weak fine subangular blocky structure; friable; many fine roots; common dark grayish distinct brown (10YR4/2) organic stains on all faces of peds; slightly acid; clear smooth boundary.

Bt1-- 18-33 cm; brown (10YR5/3) clay loam, moderate medium subangular blocky structure; friable; many fine roots; common distinct brown (10YR4/3) clay films on all faces of peds; slightly acid; clear smooth boundary.

Bt2-- 33-48 cm; yellowish brown (10YR5/4) clay, moderate medium subangular blocky structure; friable; common fine roots; common distinct brown (10YR4/3) clay films on all faces of peds; few fine distinct dark yellowish brown (10YR4/6) redoximorphic masses; neutral; clear smooth boundary.

2Bt3-- 48-64 cm; yellowish brown (10YR5/4) clay, moderate medium subangular blocky structure; firm; common fine roots; common distinct brown (10YR4/3) clay films

on all faces of peds; common fine distinct dark yellowish brown (10YR4/6) redoximorphic masses; slightly acid; clear smooth boundary.

2Bt4-- 64-94 cm; reddish gray (5YR5/2) silty clay, moderate medium subangular blocky structure; firm; common fine roots; common distinct gray (5YR5/1) clay films on all faces of peds; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; gradual smooth boundary.

2C-- 94-142 cm; gray (N5/0) silt clay, massive; few fine roots; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; gradual smooth boundary.

2Cr-- 142-203 cm; dark reddish gray (2.5YR4/1) silty clay, massive; common coarse prominent yellowish brown (10YR5/8) redoximorphic masses.

Pedon ID	Davis
Classification	Fine, kaolinitic, active, mesic, Oxyaquic Hapludults
Soil Map Unit	313E2
Location	NE1/4, Sec. 8, T70N, R12W
Land use	Conservation Reserve Program (CRP)
Hillslope position	Backslope
slope	13%
Parent material	Till or colluvium over shale

Ap-- 0-20 cm; brown (10YR4/3) silt loam, weak fine subangular blocky structure; friable; many fine roots; common dark grayish distinct brown (10YR4/2) organic stains on all faces of peds; moderately acid; abrupt smooth boundary.

Bt1-- 20-36 cm; brown (7.5YR5/4) clay, moderate fine subangular blocky structure; friable; many fine roots; common distinct brown (7.5YR4/4) clay films on all faces of peds; common fine distinct reddish brown (5YR4/4) redoximorphic masses;

- extremely acid; clear smooth boundary.
- 2Bt2-- 36-61 cm; yellowish brown (10YR5/4) clay, moderate medium subangular blocky structure; firm; common fine roots; common distinct dark yellowish brown (10YR4/4) clay films on all faces of peds; common fine distinct reddish brown (5YR4/4) redoximorphic masses; extremely acid; clear smooth boundary.
- 2BC-- 61-81 cm; grayish brown (10YR5/2) clay, moderate medium subangular blocky structure; firm; common fine roots; few distinct brown (10YR4/3) clay films on vertical faces of peds; common fine distinct reddish brown (5YR4/4) redoximorphic masses; extremely acid; gradual smooth boundary.
- 2C-- 81-112 cm; grayish brown (10YR5/2) clay, weak medium platy structure; firm; few fine roots; few distinct very pale brown (10YR8/2) silt films on vertical faces of peds; many medium prominent strong brown (7.5YR5/6) redoximorphic masses; gradual smooth boundary.
- 2Cr1-- 112-163 cm; light brownish gray (10YR6/2) clay, massive; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; gradual smooth boundary.
- 2Cr2-- 163-203 cm; black (N2.5/0) no texture because it is coal; massive.

Pedon ID	Jefferson
Classification	Fine, kaolinitic, active, mesic, Oxyaquic Hapludalfs
Soil Map Unit	313E2
Location	SE1/4, Sec. 32, T71N, R10W
Land use	Conservation Reserve Program (CRP)
Hillslope position	backslope
slope	15%
Parent material	Till or colluvium over shale

- A-- 0-13 cm; very dark grayish brown (10YR3/2) silt loam, moderate fine granular structure; friable; many fine roots; moderately acid; abrupt smooth boundary.
- E-- 13-23 cm; dark grayish brown (10YR4/2) silt loam, weak medium platy structure; friable; common fine roots; strongly acid; abrupt smooth boundary.
- Bt1-- 23-43 cm; brown (10YR4/3) clay, moderate medium subangular blocky structure; friable; common fine roots; common distinct dark grayish brown (10YR4/2) clay films on all faces of peds; common fine distinct strong brown (7.5YR5/6) redoximorphic masses; very strongly acid; clear smooth boundary.
- 2Bt2-- 43-71 cm; yellowish brown (10YR5/4) clay, moderate medium subangular blocky structure; firm; common fine roots; common distinct brown (10YR5/3) clay films on vertical faces of peds; many fine distinct strong brown (7.5YR5/6) redoximorphic masses; very strongly acid; clear smooth boundary.
- 2BC-- 71-102 cm; reddish gray (2.5YR6/1) silty clay loam, moderate medium prismatic structure; firm; few fine roots; few distinct reddish gray (2.5YR5/1) clay films on vertical faces of peds; common fine prominent light brownish gray (10YR6/8) redoximorphic masses; very strongly acid; clear smooth boundary.
- 2C1-- 102-130 cm; light bluish gray (10B7/1) silty clay, massive; firm; common fine prominent red (2.5YR5/6) redoximorphic masses; clear smooth boundary.
- 2C2-- 130-176 cm; gray (5YR5/1) clay, massive; firm; common fine distinct yellowish brown (10YR5/6) redoximorphic masses; gradual smooth boundary.
- 2C3-- 176-203 cm; reddish gray (2.5YR6/1) clay, massive; firm; common fine prominent brownish yellow (10YR6/8) redoximorphic masses.

Classification	Fine, kaolinitic, active, mesic, Oxyaquic Hapludults
Soil Map Unit	313F2
Location	NE1/4, Sec. 16, T70N, R10W
Land use	Conservation Reserve Program (CRP)
Hillslope position	backslope
slope	16%
Parent material	Till over shale

- A-- 0-10 cm; dark grayish brown (10YR4/2) loam, weak fine granular structure; friable; many fine roots; few distinct dark brown (10YR3/3) organic stains on all faces of peds; strongly acid; abrupt smooth boundary.
- E-- 10-21 cm; grayish brown (10YR5/2) loam, weak thick platy structure; friable; many fine roots; few distinct dark grayish brown (10YR4/2) organic stains on all faces of peds; strongly acid; abrupt smooth boundary.
- Bt1-- 21-41 cm; brown (7.5YR5/4) silty clay, moderate fine subangular blocky structure; friable; common fine roots; common distinct strong brown (7.5YR4/6) clay films on all faces of peds; very strongly acid; clear smooth boundary.
- 2Bt2-- 41-61 cm; pale red (2.5YR7/2) clay, moderate medium subangular blocky structure; firm; common fine roots; many distinct weak red (2.5YR5/2) clay films on all faces of peds; common fine prominent yellowish red (5YR4/6) redoximorphic masses; extremely acid; gradual smooth boundary.
- 2BC-- 61-84 cm; pinkish gray (5YR6/2) clay, weak medium subangular blocky structure; firm; common fine roots; common fine prominent strong brown (7.5YR5/6) redoximorphic masses; extremely acid; gradual smooth boundary.
- 2C1-- 84-145 cm; pale red (2.5YR7/2) loam, massive; firm; common fine roots; common

medium prominent strong brown (7.5YR5/8) redoximorphic masses; very strongly acid; gradual smooth boundary.

2C2-- 145-175 cm; pinkish gray (5YR7/2) loam, massive; firm; few fine roots; many medium prominent brownish yellow (10YR/8) redoximorphic masses; gradual smooth boundary.

2Cr-- 175-203 cm; gray (N6/0) silty clay, massive; firm; common medium prominent brownish yellow (7.5YR4/4) redoximorphic masses.

Pedon ID	Keokuk
Classification	Fine, kaolinitic, active, mesic, Oxyaquic Hapludalfs
Soil Map Unit	313F2
Location	NW1/4, Sec. 30, T75N, R12W
Land use	Pasture
Hillslope position	backslope
slope	20%
Parent material	Till over shale

Ap-- 0-13 cm; brown (10YR4/3) loam, moderate fine granular structure; friable; many fine roots; few distinct dark grayish brown (10YR4/2) organic stains on all faces of peds; strongly acid; abrupt smooth boundary.

2Bt1 13-36 cm; yellowish brown (10YR5/4) clay, moderate medium subangular blocky structure; firm; many fine roots; few distinct dark grayish brown (10YR4/2) organic stains on all faces of peds; common distinct brown (10YR5/3) clay films on all faces of peds; very strongly acid; clear smooth boundary.

2Bt2-- 36-61 cm; yellowish brown (10YR5/4) clay, moderate medium subangular blocky structure; firm; common fine roots; few distinct dark grayish brown (10YR4/2)

organic stains on vertical faces of peds; common distinct grayish brown (10YR5/2) clay films on all faces of peds; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; very strongly acid; clear smooth boundary.

- 2BC -- 61-94 cm; dark reddish gray (2.5YR4/1) silty clay, moderate medium subangular blocky structure; firm; common fine roots; common distinct dark reddish gray (2.5YR3/1) clay films on top faces of peds; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; strongly acid; gradual smooth boundary.
- 2C1-- 94-112 cm; dark reddish gray (2.5YR3/1) silty clay, massive; firm; common fine roots; few distinct very pale brown (10YR8/2) silt films; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; strongly acid; gradual smooth boundary.
- 2C2-- 112-135 cm; yellowish brown (10YR5/4) silty clay loam, massive; firm; common fine roots; few distinct very pale brown (10YR8/2) silt films; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; gradual smooth boundary.
- 2Cr1-- 135-152 cm; dark reddish gray (2.5YR3/1) soft shale; few fine roots.

Pedon ID	Lucas
Classification	Fine, mixed, active, mesic, Oxyaquic Hapludalfs
Soil Map Unit	313E2
Location	SW1/4, Sec. 12, T73N, R20W
Land use	Pasture
Hillslope position	backslope
slope	16%
Parent material	Till or colluvium over shale

- Ap-- 0-20 cm; brown (10YR4/3) silty clay loam, weak fine subangular blocky structure; friable; many fine roots; few distinct dark brown (10YR3/3) organic stains on all faces of peds; strongly acid; abrupt smooth boundary.
- 2Bt1 20-40 cm; light reddish brown (2.5YR6/3) silty clay, moderate medium subangular blocky structure; firm; common fine roots; common distinct weak red (2.5YR5/2) clay films on all faces of peds; common fine prominent yellowish brown (10YR5/6) redoximorphic masses; strongly acid; clear smooth boundary.
- 2Bt2-- 40-50 cm; weak red (2.5YR5/2) clay, moderate medium subangular blocky structure; firm; common fine roots; many distinct dark reddish gray (2.5YR4/1) clay films on all faces of peds; common fine prominent yellowish brown (10YR5/6) redoximorphic masses; moderately acid; clear smooth boundary.
- 2BC -- 50-69 cm; gray (N5/0) silty clay, massive; firm; common fine roots; common distinct dark gray (N4/0) clay films on vertical faces of peds; common medium prominent brown (7.5YR4/4) redoximorphic masses; moderately acid; gradual smooth boundary.
- 2C1-- 69-99 cm; gray (N5/0) silty clay, massive; firm; common fine roots; few distinct white (10YR8/1) silt films on vertical faces of peds; many coarse prominent strong brown (7.5YR5/6) redoximorphic masses; gradual smooth boundary.
- 2C2-- 99-122 cm; gray (N6/0) silty clay, massive; firm; common fine roots; few distinct white (10YR8/2) silt films on vertical faces of peds; common medium prominent strong brown (7.5YR5/6) redoximorphic masses; gradual smooth boundary.
- 2C3-- 122-178 cm; gray (N6/0) soft shale and coal; massive; many coarse prominent strong brown (7.5YR5/6) redoximorphic masses; few fine roots.

Pedon ID	Marion
Classification	Fine, mixed, active, mesic, Oxyaquic Hapludults
Soil Map Unit	313E2
Location	SE1/4, Sec. 18, T57N, R6W
Land use	Pasture
Hillslope position	backslope
slope	17%
Parent material	Till or colluvium over shale
Ap--	0-20 cm; brown (10YR4/3) silty clay loam, weak fine subangular blocky structure; friable; many fine roots; few distinct dark brown (10YR3/3) organic stains on all faces of peds; moderately acid; abrupt smooth boundary.
2Bt1	20-33 cm; pale brown (10YR6/3) silty clay, moderate fine subangular blocky structure; firm; common fine roots; common distinct weak red (2.5YR5/2) clay films on all faces of peds; common fine distinct yellowish brown (10YR5/6) redoximorphic masses; strongly acid; clear smooth boundary.
2Bt2--	33-64 cm; weak red (2.5YR5/2) clay, moderate medium subangular blocky structure; firm; common fine roots; many distinct dark reddish gray (2.5YR4/1) clay films on all faces of peds; common fine prominent strong brown (7.5YR5/6) redoximorphic masses; very strongly acid; gradual smooth boundary.
2BC --	64-102 cm; gray (N6/0) clay, weak fine subangular blocky structure; firm; common fine roots; common distinct gray (N5/0) clay films on vertical faces of peds; many medium prominent strong brown (7.5YR5/6) redoximorphic masses; very strongly acid; gradual smooth boundary.
2C--	102-156 cm; gray (N5/0) clay, massive; firm; few fine roots; very few distinct white (10YR8/1) silt films on vertical faces of peds; many medium prominent

strong brown (7.5YR5/6) redoximorphic masses; extremely acid; abrupt smooth boundary.

2Cr-- 156-173 cm; black (N2.5/0) clay, massive; firm.

Appendix 2

Materials and methods used in chapter 4

Particle size analysis

Soil texture was determined by the pipette method (Pansu and Gautheyrou, 2006). From each oven-dried soil sample, 10 g were weighed into 500-mL glass bottles. All of the weighed samples were wetted with distilled water. To fulfill the dispersion step of the samples, 5mL of 1% acetic acid and 10 mL of hydrogen peroxide (H_2O_2) were added in order to remove both calcium carbonates (CaCO_3) and organic matter; additional amounts of both of the two reagents were added as needed. All of the samples were warmed up (but no boiling) on a hot plate at low temperatures in order to accelerate the reactions. Next, we removed all excess cations in the sample solution by washing with distilled water. More specifically, we added distilled water to every beaker, stirred the contents, left them overnight and then decant the supernatant. We repeated this step until the contents became partially suspended. Ten ml of sodium hexametaphosphate were added to each bottle contents in order to complete the dispersion step. All of the samples were shaken overnight and then they were sieved to separate sand fraction from both silt and clay fractions. Silt and clay fractions in the suspension were isolated from each other according to Stokes' Law.

Cation exchange capacity

Cation exchange capacity (CEC) was measured by Na-saturation displacement using the centrifuge method (Soil Survey Staff, 2004). Five g of each sample was washed by 33 ml of 1N sodium acetate (NaOAc) solution at pH 8.2, in order to displace all of the cations on the exchangeable complex by Na. NaOAc washing step was repeated two more times. The excess Na ions were washed by 33ml of 95% denatured ethanol. Ethanol washing step was

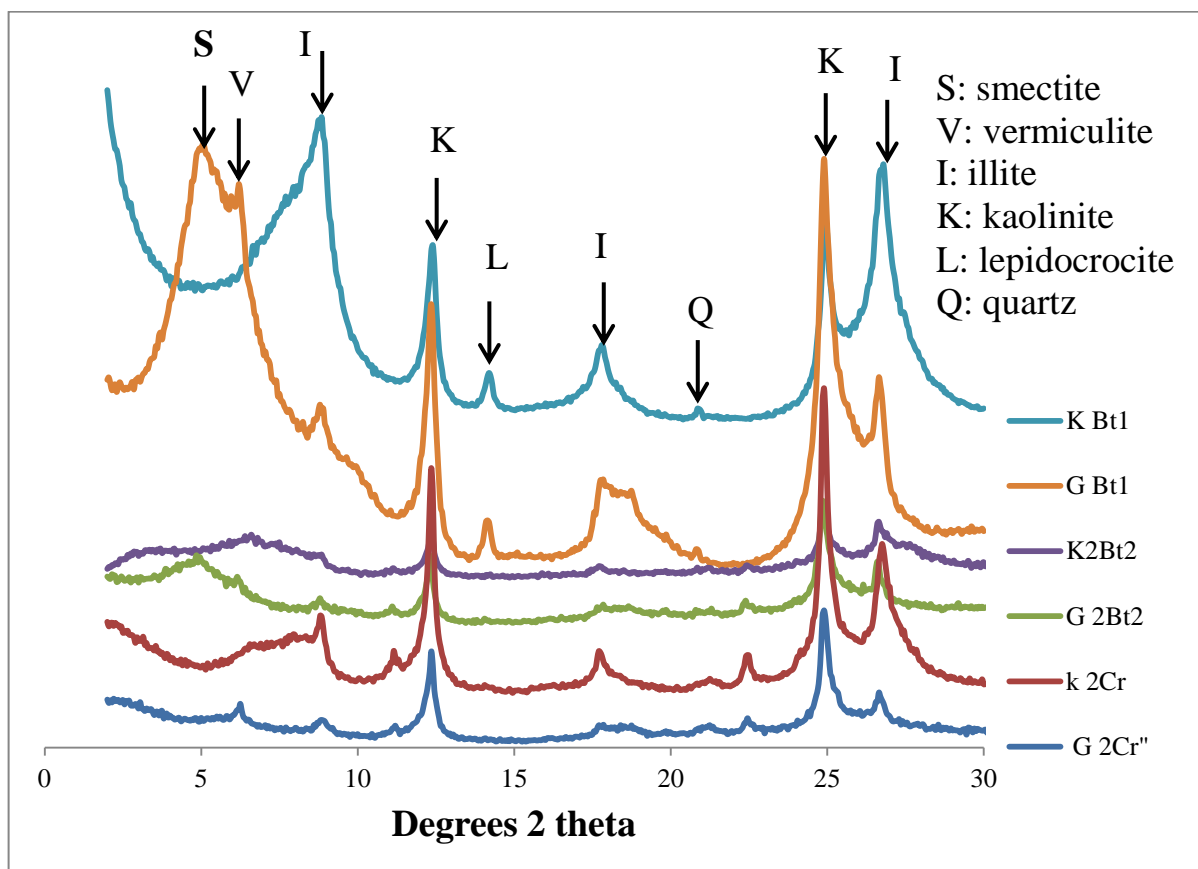
repeated two more times. Then the Na ions on the exchange complex were displaced with 33 ml of 1N ammonium acetate (NH_4OAc) at pH 7.0. The displacing by 1N NH_4OAc was repeated two more times. The supernatant was collected in 100 ml volumetric flasks, which were filled to volume by adding 1N NH_4OAc . The resulting concentration of Na ions was determined using an Analyst 100 atomic absorption spectrometer (PerkinElmer Instruments, 2009). Dilutions were prepared as needed.

Base saturation

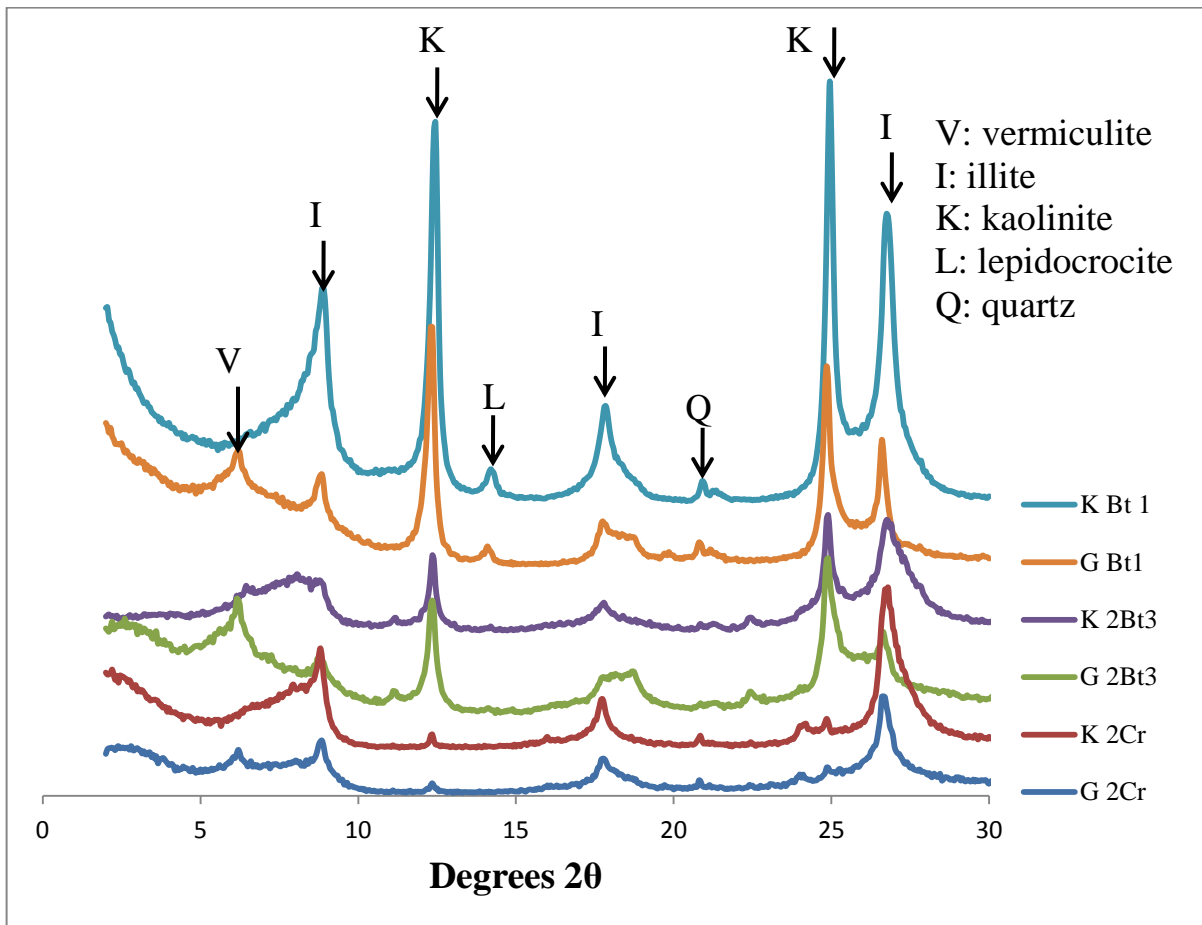
Base saturation was determined by extracting Ca^{2+} , Mg^{2+} , Na^+ and K^+ by displacement with 1N NH_4OAc at pH 7.0. Five g of each soil sample was weighed, saturated by 33 ml of 1N NH_4OAc , shaken for five minutes and then centrifuged at 3000 rpm for five minutes. The supernatant was collected in 100 ml volumetric flasks. Displacement step was repeated two more times and the volumetric flasks were filled to volume with 1N NH_4OAc . The four cations were measured using Inductively Coupled Plasma Mass Spectrophotometry (ICP), (Soil Survey Staff, 2004). Percent base saturation was calculated by dividing the sum of the base cations of each sample by CEC of the same sample and then multiplying the result by a 100.

Appendix 3

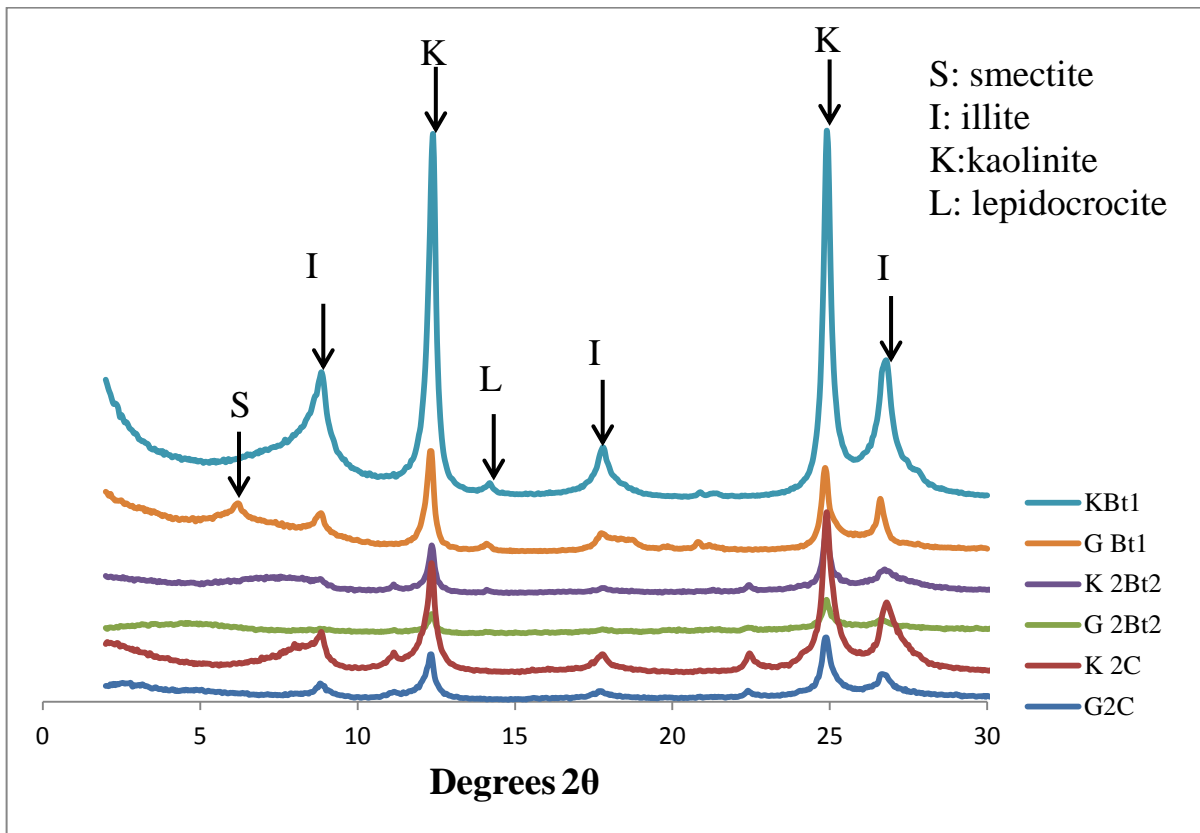
X-ray diffraction patterns of study pedons



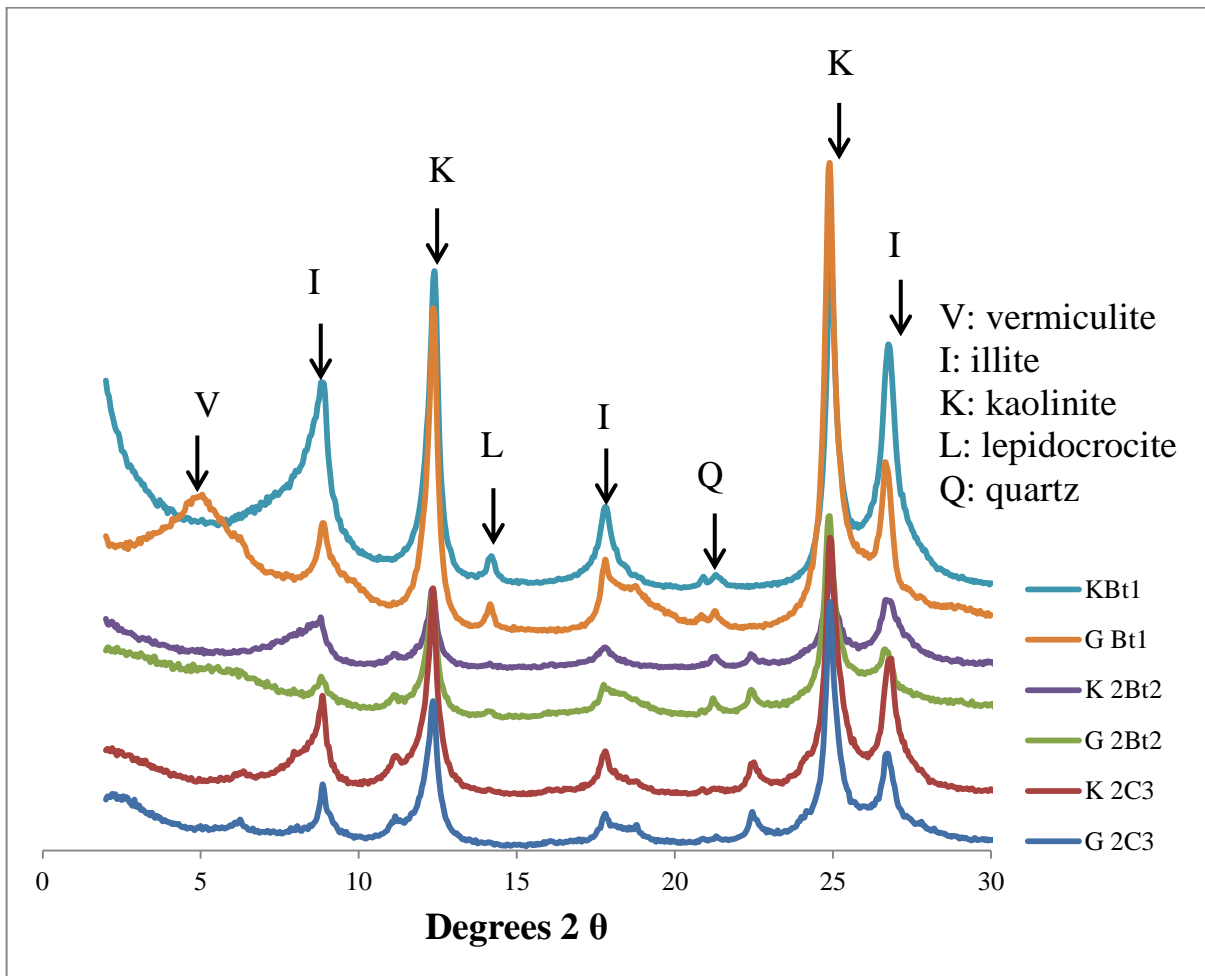
X-ray diffraction patterns of Mahaska pedon.



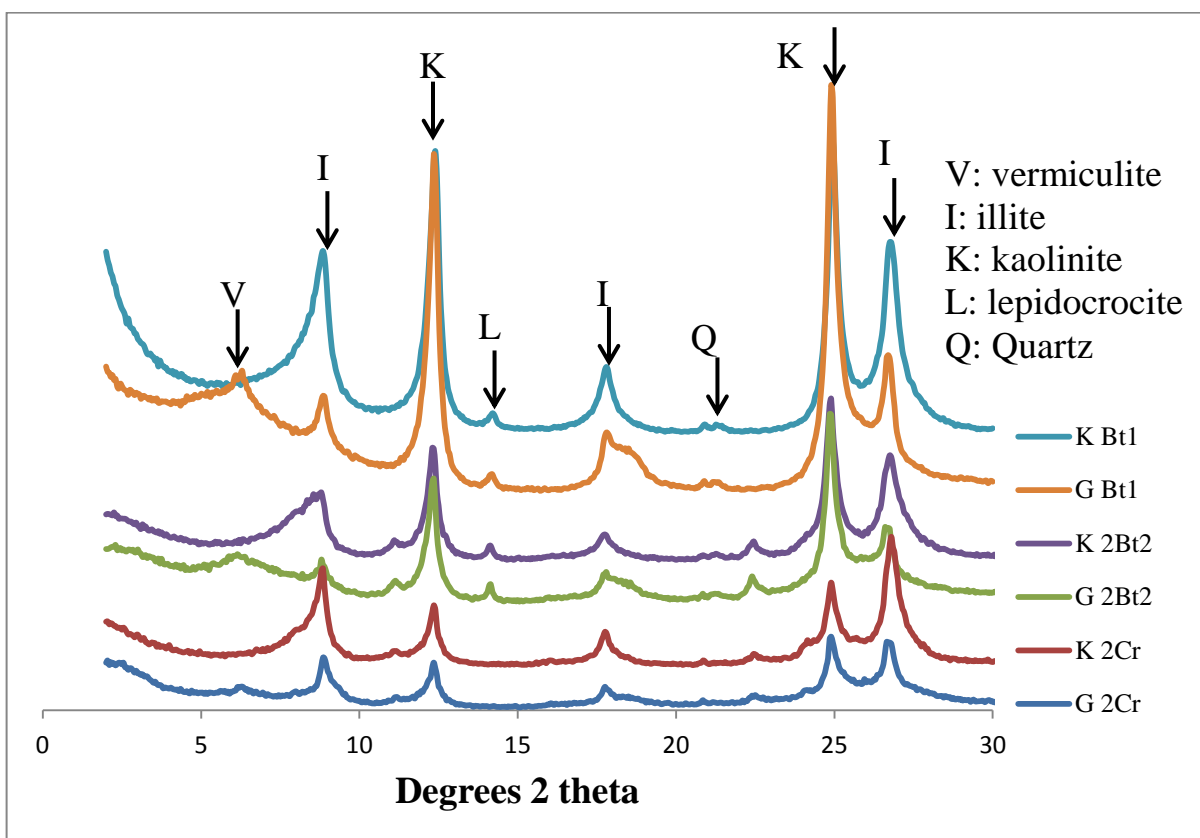
X-ray diffraction patterns of Monroe pedon.



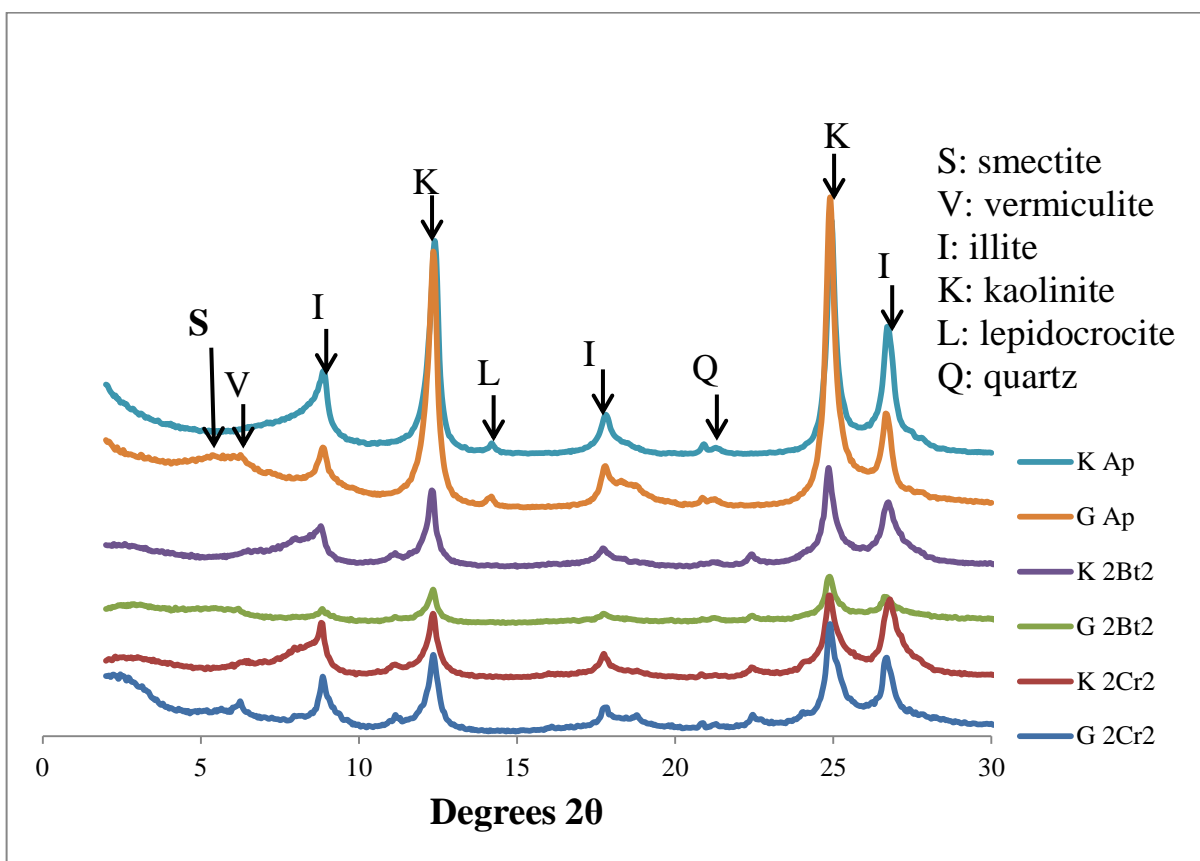
X-ray diffraction patterns of Davis pedon.



X-ray diffraction patterns of Jefferson pedon.



X-ray diffraction patterns of Van Buren pedon.



X-ray diffraction patterns of Keokuk pedon.

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